Ministry of Natural Resources

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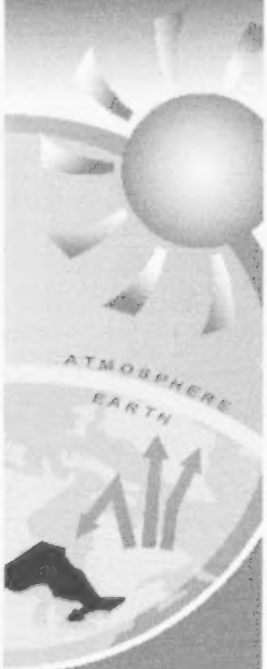
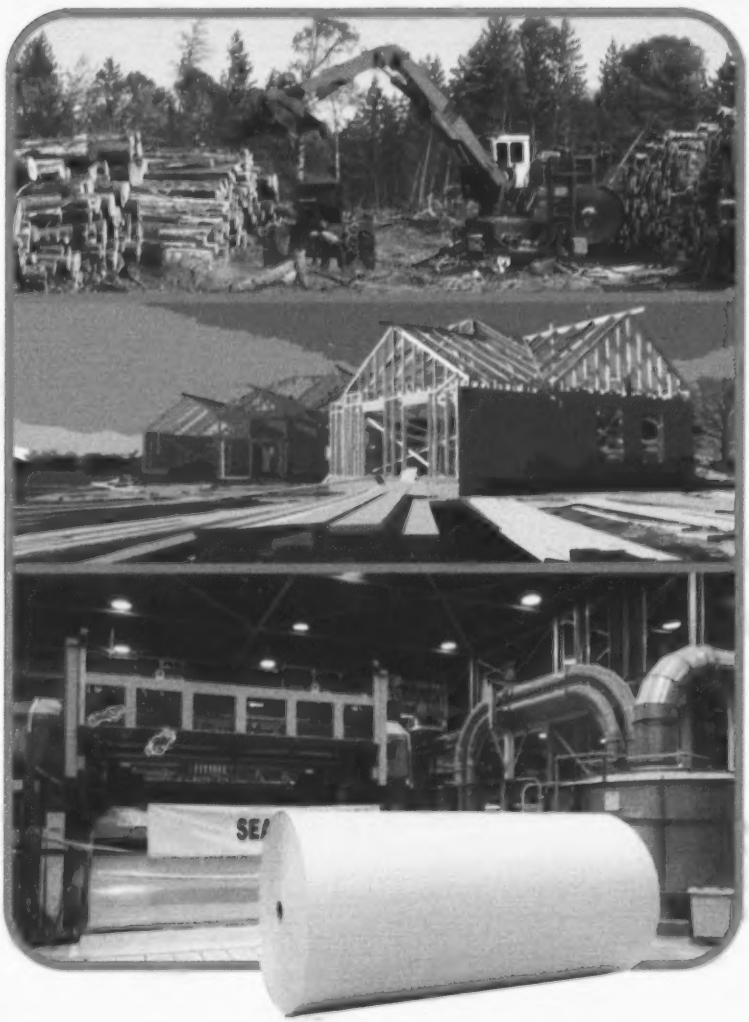
CLIMATE CHANGE RESEARCH REPORT CCRR-33



Responding to Climate Change Through Partnership

Carbon Stocks and Flows from Harvest to Disposal in Harvested Wood Products from Ontario and Canada



Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change

MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change

MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt

MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

Carbon Stocks and Flows from Harvest to Disposal in Harvested Wood Products from Ontario and Canada

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Summary

In this report, we systematically analyze the biomass carbon (C) conversion of harvested wood products (HWPs) produced from forests in Ontario and, more broadly, in Canada. The major categories of HWPs referred to are lumber, structural panel, non-structural panel, market pulp, newsprint, fine paper, and "other" paper products. Our analysis tracks C flow for each product type from forest to harvested biomass, re-allocation of biomass C among HWPs, use of wood residue to produce energy, exports of HWPs from Ontario and Canada, and distribution of HWPs among major end uses. As well, service lives of HWPs, end-of-life disposal, and landfill HWP C stock and landfill methane (CH_4) emissions for HWPs produced and used in Ontario/Canada and in countries that import HWPs from Ontario/Canada are assessed.

Based on biomass conversion efficiencies of the manufacturing processes for major HWPs, and the use of biomass residue to produce energy, we estimated that from 1999 to 2010, on average, 35% of the biomass harvested from Ontario's forests was converted to solid HWPs, of which 25, 8, and 2% is in lumber, structural panel, and non-structural panel products, respectively. Pulp production accounted for 26% of harvested biomass in Ontario, divided between chemical and mechanical pulp at rates of 46 and 54%, respectively. Overall, 61% of the tree biomass harvested in Ontario was converted to various HWPs. Of the remaining biomass harvested, 29% was used to produce bioenergy and 10% was lost to decomposition, residue burning without energy recovery, or disposed of in landfills and stockpiles.

At the national level, we estimated that 65% of the harvested biomass was converted to HWPs: 32, 4, 6, and 23% in lumber, structural panel, non-structural panel, and pulp, respectively. Energy production consumed an additional 26% of harvested biomass and 9% of the harvested biomass was decomposed, burned without producing energy, or discarded in landfills.

Most of Ontario's and Canada's HWPs are shipped to foreign markets, primarily the United States. We estimated that between 1991 and 2010, on average, 63% of Ontario's HWPs were exported. Exports accounted for 64% of the solid HWPs produced in Canada between 2005 and 2010, and 86% of pulp, paper, and paper products produced between 1991 and 2010. The types of uses of HWPs and methods of their disposal, which varies among jurisdictions, can significantly affect the amount of C in HWPs in use and the conversion of that C along various disposal pathways.

The end use of a HWP significantly affects its time in service. The construction industry is the single most important user of solid HWPs, estimated to consume 64% of lumber, 76-77% of structural panels, and 41% of non-structural panels produced in Ontario and Canada.

Major end uses of paper products produced from wood harvested in Ontario were estimated to be 33, 32, 28, and 7% for newsprint, printing and writing paper, wrapping and packaging paper, household and sanitary paper and other paper and paper products, respectively. Fractions at the national level were similar.

Half-life is the number of years it takes to lose one-half of the initial wood biomass of a HWP from its original end use. Solid HWPs used for the construction of single family houses, multi-family houses, and residential repair and remodelling in the United States were estimated to have half-lives of 85, 50, and 25 years, respectively, compared to a 2.5 year half-life for paper and paper products.

Retired HWPs undergo different disposal pathways: recycling and reuse that continue to store C; burning with or without energy recovery that results in immediate C release; and disposal, mainly in landfills. Prior to 1950, almost all retired HWP were either burned without energy recovery (30%) or disposed of in open dumps (>63%). Until 1970, burning and disposal in open dumps remained the main disposal methods in North America. Since then, landfills quickly replaced open dumps, with 68% of retired solid HWPs and 52% of paper and paper products produced by the Canadian forestry sector disposed of in landfills by 1980. Recycling has extended the use of Canadian paper and paper products, with the recycling rate increasing from 21% in 1980 to 66% in 2009. The increase in paper recycling reduced the fraction of landfilled paper and paper products from 52% in 1980 to 12% in 2009.

Modern landfills create an anaerobic environment in which a portion of HWPs decompose extremely slowly or not at all. Of the total HWP C that decomposes in landfills, half is converted to CH_4, which has 25 times the global warming potential of carbon dioxide (CO_2). Collection and combustion of landfill CH_4 increased from 21% in 1990 to 29% in 2009 in Canada and from 10% to 54% during the same period in the United States. Of the remaining CH_4 generated in landfills, from 10% to 36% of it is oxidized by bacteria in the soil covering the waste. We assumed CH_4 capture rates increase by 0.2% each year, resulting in 64 and 66% of CH_4 generated from Canadian solid HWPs and paper products, respectively, in landfills being captured and converted to CO_2 after a 100-year period.

Based on our analysis of HWP decomposition in landfills, and associated CH_4 generation, collection, and oxidization (10%), we produced two examples of landfill C stocks and CH_4 emissions for solid HWPs and paper and paper products produced by the Canadian forestry sector. Assuming annual disposal of 1 tonne of HWP C from either solid HWPs or paper products over a 100-year period, solid HWP disposal accumulates 231 tonnes of CO_2 equivalent (CO_2eq) at the end of 100 years, while paper and paper products disposal in landfills results in a net emission of 50 tonnes of CO_2eq over 100 years. Thus, the net C stock/emission from Canadian HWPs placed in landfills depends largely on the mix of products.

The information in this report can be used to estimate future potential HWP C stocks and emissions for the forestry sector in Ontario and Canada. As major global producers of wood products, an understanding of Ontario's and Canada's HWP stocks and emissions is needed to determine what is important when evaluating the overall contribution of forests to efforts to mitigate global climate changes.

Somaire : Stocks et flux de carbone, du prélèvement d'arbres à l'élimination des produits du bois provenant de l'Ontario et du Canada

Nous avons analysé systématiquement la conversion du carbone de la biomasse des produits du bois (PB) issus des forêts de l'Ontario en particulier et des forêts du Canada en général. Dans le présent rapport, les principales catégories de PB sont le bois d'œuvre, les panneaux de grandes particules, les panneaux non structuraux, la pâte commerciale, le papier journal, le papier fin et divers « autres » produits papetiers. Pour chaque type de PB, nous avons suivi le flux de carbone de la forêt à la biomasse exploitée et examiné la réattribution du carbone de la biomasse entre les PB, l'exploitation des résidus ligneux pour la production d'énergie, les PB exportés de l'Ontario et du Canada, et la répartition des PB entre leurs principales utilisations finales. Nous avons également examiné la durée de vie utile des PB, l'élimination des PB à la fin de leur vie utile, le carbone des PB que stockent les décharges et les émissions de méthane (CH4) que produisent les décharges, pour les PB produits et utilisés en Ontario, au Canada et dans les pays qui importent des PB de l'Ontario ou d'autres endroits au Canada.

Selon le degré d'efficacité de conversion de la biomasse qu'ont les procédés manufacturiers pour les principaux BP, et l'exploitation des résidus de biomasse pour la production d'énergie, nous avons estimé qu'en moyenne, entre 1999 et 2010, 35 % de la biomasse prélevée des forêts ontariennes a été convertie en PB solides, constitués de bois d'œuvre (25 %), de panneaux de grandes particules (8 %) et de panneaux non structuraux (2 %). La production de pâte représentait 26 % de la biomasse prélevée des forêts ontariennes. Elle était constituée de pâte chimique (46 %) et de pâte mécanique (54 %). Dans l'ensemble, 61 % de la biomasse prélevée des forêts ontariennes a été convertie en divers PB. Pour ce qui est du reste de la biomasse prélevée, 29 % a servi à produire de la bioénergie et 10 % a été perdu par décomposition, brûlage de résidus (sans récupération d'énergie) ou élimination dans des décharges contrôlées ou des amas.

À l'échelle nationale, nous avons estimé que 65 % de la biomasse prélevée a été convertie en PB, répartis comme suit : bois d'œuvre (32 %), panneaux de grandes particules (4 %), panneaux non structuraux (6 %) et pâte (23 %). La production d'énergie a représenté 26 % de la biomasse prélevée, et 9 % de la biomasse a été perdue par décomposition, brûlage (sans production d'énergie) ou élimination dans des décharges.

La plupart des PB de l'Ontario et du Canada sont expédiés vers des marchés étrangers, principalement les États-Unis. Nous avons estimé qu'en moyenne, entre 1991 et 2010, 63 % des PB de l'Ontario ont été exportés. Les exportations représentaient 64 % des PB solides produits au Canada entre 2005 et 2010. Entre 1991 et 2010, elles représentaient 86 % de la pâte, du papier et d'autres produits papetiers. Les sortes d'utilisations des PB et les méthodes d'élimination des PB, lesquelles varient selon les territoires, peuvent avoir une forte incidence sur la teneur en carbone des PB en usage et sur la conversion de ce carbone le long de la chaîne d'élimination.

L'utilisation finale d'un PB se répercute de façon importante sur sa durée de vie utile. Le secteur de la construction est le plus important utilisateur de PB solides. Nous avons estimé qu'il utilise 64 % de bois d'œuvre, de 76 à 77 % de panneaux structuraux et 41 % de panneaux non structuraux produits en Ontario et ailleurs au Canada.

Pour ce qui est des principales utilisations finales des produits papetiers issus du bois d'origine ontarienne, nous avons estimé qu'elles se répartissent comme suit : papier journal (33 %), papier impression et papier écriture (32 %), et papier d'emballage (28 %). Le reste (7 %) est constitué de papiers sanitaires et ménagers, et d'autres produits papetiers. Les pourcentages sont semblables à l'échelle nationale.

La demi-vie est le nombre d'années qu'il faut pour qu'un PB perdre la moitié de sa biomasse dans le cadre de son utilisation finale initiale. D'après les estimations, les BP solides qui sont utilisés aux États-Unis pour la construction de logements individuels, la construction de logements multifamiliaux et les travaux de réparation et de rénovation auraient une demi-vie de 85 ans (logements individuels), de 50 ans (logements multifamiliaux) et de 25 ans (travaux de réparation et de rénovation). Par comparaison, les papiers et les produits papetiers auraient une demi-vie de 2,5 ans.

Les PB retirés de leur utilisation finale ont différents modes d'élimination : le recyclage et la réutilisation qui continuent de stocker du carbone, le brûlage (avec ou sans récupération d'énergie) qui libère tout de suite du carbone et la destruction, principalement dans des décharges contrôlées. Avant 1950, presque tous les PB retirés de leur utilisation finale étaient soit brûlés sans récupération d'énergie (30 %), soit jetés dans des dépotoirs à ciel ouvert (plus de 63 %). Jusqu'à 1970, le brûlage et l'élimination dans des dépotoirs à ciel ouvert étaient les principaux modes d'élimination en Amérique du Nord. Depuis, les décharges ont vite remplacé les dépotoirs à ciel ouvert. En 1980, c'est dans des décharges qu'étaient éliminés 68 % des PB solides retirés de leur utilisation finale et 52 % du papier et des produits papetiers issus du secteur forestier du Canada. Le recyclage a permis d'accroître l'utilisation du papier et des produits papetiers du Canada. Le taux de recyclage du papier et des produits papetiers est passé de 21 % en 1980 à 66 % in 2009. Grâce à l'accroissement du taux de recyclage du papier, la quantité de papier et de produits papetiers éliminés dans des décharges a été ramenée de 52 % en 1980 à 12 % en 2009.

Les décharges modernes créent un milieu anaérobie dans lequel une partie des PB se décompose très lentement ou ne se décompose pas du tout. Du carbone des PB qui se décomposent dans les décharges, 50 % est converti en méthane (CH_4), dont le potentiel de réchauffement global est 25 fois celui du dioxyde de carbone (CO_2). Au Canada, la collecte et le brûlage du méthane que produisent les décharges ont augmenté de 21 % en 1990 à 29 % en 2009. Aux États-Unis durant cette même période, ils sont passés de 10 % à 54 %. Du reste du méthane que produisent les décharges, de 10 à 36 % est oxydé par les bactéries du sol qui recouvrent les déchets. En présumant que le taux de captage du méthane aurait augmenté de 0,2 % chaque année, nous avons estimé que 64 % des BP solides et 66 % des produits papetiers d'origine canadienne que renferment les décharges seraient captés et convertis en dioxyde de carbone au bout d'une période de 100 ans.

D'après notre analyse de la décomposition des PB dans les décharges, et celle de la production, de la collecte et de l'oxydation du méthane associé à la décomposition des PB, nous avons produit deux exemples de stockage de carbone dans les décharges et d'émissions de méthane pour les PB et les produits papetiers (dont le papier) provenant du secteur forestier du Canada. En présumant un taux d'élimination annuel des BP de 1 tonne de carbone (BP solides et produits papetiers) sur une période de 100 ans, l'élimination des PB aurait produit, au bout de cette période de 100 ans, un stock d'équivalent CO2 de 231 tonnes (231 TeqCO2) et celle des produits papetier aurait produit une émission nette d'équivalent CO2 de 50 tonnes (50 TeqCO2). Par conséquent, les émissions et les stocks de carbone nets provenant des PB d'origine canadienne qui sont enfouis dans les décharges sont en grande partie déterminés par le mélange de produits.

Les données présentées dans le présent rapport peuvent être utilisées par le secteur forestier en Ontario et au Canada pour estimer le potentiel des émissions et des stocks de carbone provenant des PB. L'Ontario et le Canada étant de grands producteurs de PB, l'analyse des émissions et des stocks de carbone est requise pour mieux comprendre les facteurs importants dans l'estimation de la contribution globale que les forêts apportent aux efforts faits pour atténuer le changement climatique.

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Acronyms

C	Carbon
CCFM	Canadian Council of Forest Ministers
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CTL	Cut to length harvesting
EU27	The 27 countries in the European Union
FAO	Food and Agriculture Organization of the United Nations
FT	Full tree harvesting
FT-CH	Harvesting method of full tree to roadside chips to mill
FT-SW	Harvesting method of full tree to roadside and shortwood to mills
FT-TL	Harvesting method of full tree to roadside tree length to mill
GHG	Greenhouse gas
HWPs	Harvested wood products
IPCC	Intergovernmental Panel on Climate Change
MDF	Medium-density fibreboard
MLL	Multiple log length
Mt	Million tonnes
NRCan	National Resources Canada
ODT	Oven-dry tonne (0% moisture content)
OMNR	Ontario Ministry of Natural Resources
OSB	Oriented strand board
TL	Tree length harvesting
UNFCCC	United Nations Framework Convention on Climate Change
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency

1. Introduction

In its fourth assessment report, the Intergovernmental Panel on Climate Change (IPCC) concluded that climate warming is unequivocal and that recent increases in global average temperatures are due to anthropogenic emission of greenhouse gases (GHG; IPCC 2007a). The IPCC also concluded that continued human-caused GHG emissions at or above current rates would cause warming that could result in harmful changes in global climate.

Forestry has the potential to contribute significantly to mitigating global climate change while simultaneously ensuring forests are adapted to climate change and thereby supporting sustainable resource development (IPCC 2007c). Forestry-related mitigation options include reducing carbon (C) emissions caused by deforestation and forest degradation, enhancing the C sequestration rate of forests, providing wood fuels as a substitute for fossil fuels, and using harvested wood products (HWPs) to replace more energy-intensive materials.

Canada has 397 million hectares of forest, representing 10% of the world's forest (Natural Resources Canada 2012). With its major share of global forests, Canada has been one of the largest HWP producers and exporters in the world (FAO 2011; Tables 4-5, p. 128-149). The C stocks in use for Canadian HWPs increased by 16.1 million tonnes (Mt) in 1990 and 21.9 Mt in 2005 (Upton et al. 2007). While Canada is committed to sustainably producing significant amounts of HWPs that result in increased C stocks, Canada's forestry sector has also reduced its fossil fuel consumption by using wood bioenergy from harvest and processing residues to run its operations (Natural Resources Canada 2012).

Ontario's forests account for 17.9% of Canada's total forest area, producing about 13% of the industrial roundwood harvested in Canada between 1999 and 2010. Thus, Ontario's HWP industries are also important to climate change mitigation efforts. Accurately assessing the mitigation potential of Ontario's and Canada's forestry sector requires understanding the flow of biomass C harvested and how it is dispersed through the manufacturing processes of major HWP types. Such estimates also need to account for the use of mill residue to produce value-added HWPs and bioenergy, end uses by major consumers, and final disposal.

Despite the potential importance of Canadian HWPs in the mitigation of global climate change, little research in this area is reported in the literature (Griss 2009). A comprehensive biomass conversion analysis for Canadian HWPs was conducted using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS; Kurz et al. 1992). This model accounts for harvest-induced forest C stock changes, tracks harvested biomass from the time it enters the forestry sector until it is released to the atmosphere, and estimates the biomass used to produce energy in HWP industries. However, as acknowledged by Kurz et al. (1992), when the model was developed tracking of harvested biomass conversion was largely based on expert judgement or very limited data. Estimating HWP C stocks/emissions remains a research need (Kurz et al. 2009).

Upton et al. (2007) produced C and GHG profiles for Canada's forestry sector primarily based on summarized industrial statistics. In this study, GHG emissions from HWP production facilities were estimated using facility fossil fuel combustion (obtained from industry surveys) multiplied by the GHG emission factors of each fuel type. However, Upton et al. (2007) lacked information about biomass C conversions during HWP manufacturing. Therefore, the results reported by Upton et al. (2007) are difficult to use in forest C models, such as CBM-CFS3 and FORCARB-ON (Chen et al. 2010), which require detailed and process-specific analysis and parameters to assess GHG effects for different HWP types.

In an Ontario-specific study (Chen et al. 2008, 2010), we reported our HWP C modelling approach and the key parameters that were incorporated in the FORCARB-ON model. We used data published in recent years (e.g., UNFCCC 2003, Skog et al. 2004, US EPA 2007) and new modelling approaches (e.g., UNFCCC 2003, IPCC 2006) to estimate C storage and emissions for HWPs in use and discarded in landfills. This report builds on that earlier work by updating analyses on biomass C conversion during HWP manufacturing at both the provincial and national levels, and estimating landfill methane (CH_4) emission and collection to produce energy.

In this report, we provide a quantitative analysis of forest biomass C conversion by industrial process in the HWP sector of Ontario and Canada, and develop parameters to estimate the conversion of forest biomass to

HWP C stocks for these jurisdictions. Unless otherwise indicated, the information presented/used for analysis in this report is for the 1999-2010 period. We analyzed HWP C stocks and emissions for major stages (Figure 1): C conversion during the production stage (forestry sector analysis), C stock of HWPs in use (end use analysis), and C conversion after HWPs reach the end of their service lives (end-of-life analysis). Our results describe: (i) analysis of Canadian HWPs industry manufacturing processes, (ii) parameter estimates for converting biomass C from forest to harvested roundwood, from roundwood to finished HWP, and from finished HWP to major end uses, (iii) fates of HWPs, including length of service life and disposal methods (recycling, energy recovery, burned as waste, disposed of in landfills), (iv) parameter estimates for HWP C retention in use and in landfills, and (v) rates of CH_4 production, i.e., generation, capture, oxidation, and emission, of HWPs disposed of in landfills.

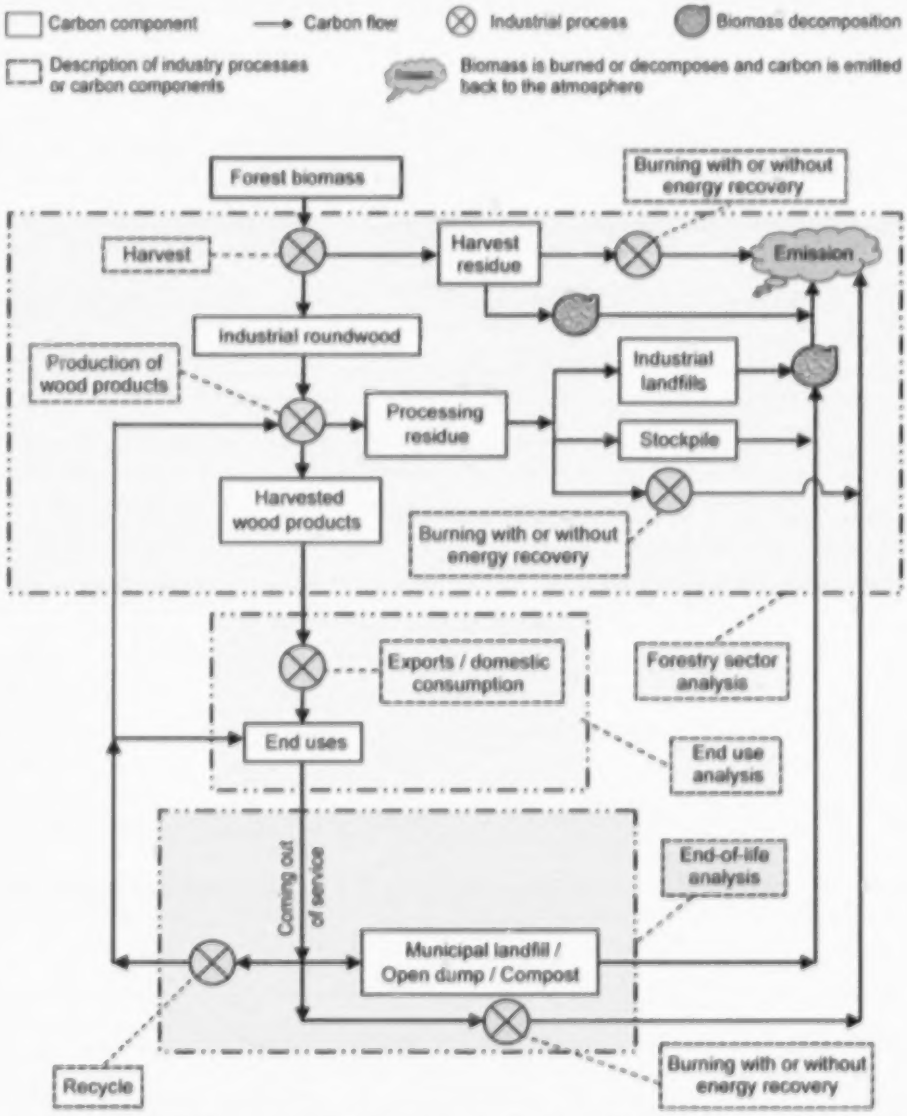

Figure 1. *Biomass carbon conversion of harvested wood in the three major life stages of harvested wood products (HWPs). Note: Major life stages of HWPs include production, end use, and disposal.*

2. Forestry sector analysis – biomass carbon re-allocation during forest harvesting and wood product manufacturing

The flow of harvested forest biomass C into finished HWPs, starting from forest harvesting and field processing of the harvested wood (industrial roundwood), is illustrated in Figure 2. Harvested wood then follows one of two paths: solid HWP manufacturing or pulp and paper production. When solid HWPs are produced, a significant portion of industrial roundwood biomass is converted to pulp chips as a by-product. Any wood residue not suitable for use as pulp chips from various HWP manufacturing processes is commonly used to produce energy to replace fossil fuels, especially in the more energy intensive pulp and paper industry (National Energy Board 2010).

Harvest residue left on harvest sites can provide wildlife habitats and nutrition for forest regeneration, with its C slowly released through decomposition. But this is beyond the scope of the present study. Burning slash piles on site will immediately release their C (Figures 1 and 2), but only affects forest C stock and thus, will not be discussed

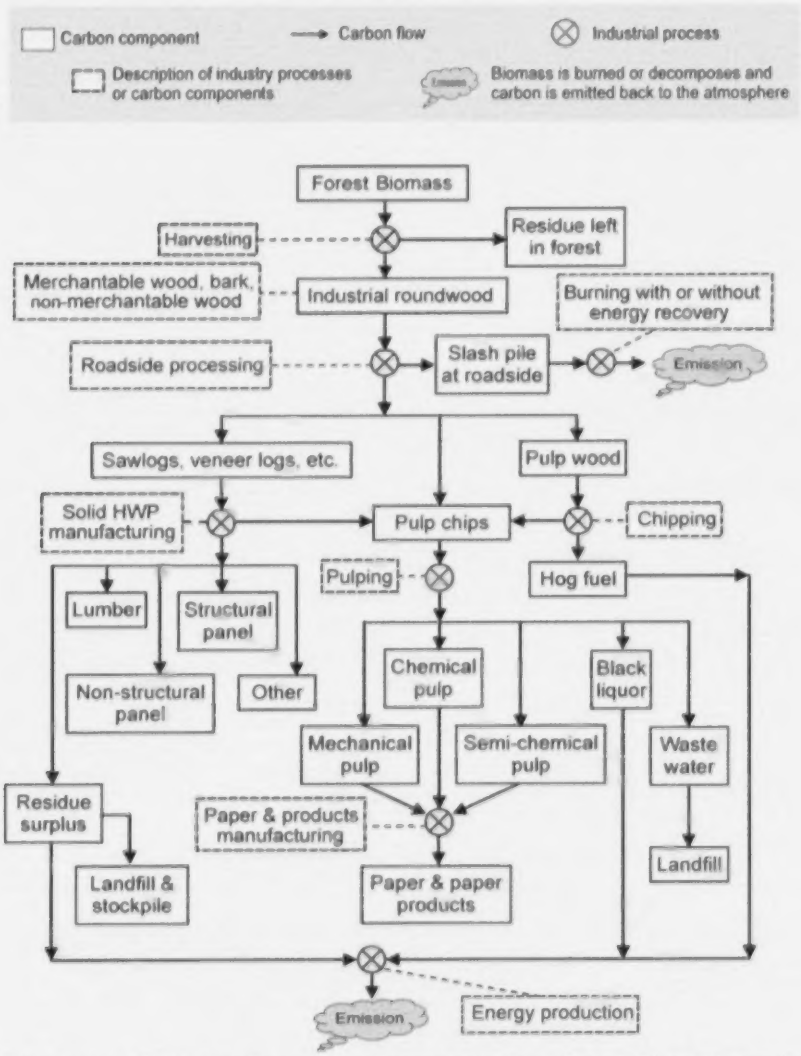

Figure 2. *Major industrial processes between wood harvesting and harvested wood product (HWP) manufacture (i.e., end use, disposal, and decomposition of slash piles at roadside or in landfill not included).*

in the report. Collecting harvest residue for producing energy appears to be an emerging option for reducing GHG emissions from burning fossil fuels, at the cost of increasing harvest impacts on forest ecosystem; the trade-offs need to be fully assessed as a future research need.

2.1. Estimating biomass carbon of industrial roundwood

Industrial roundwood harvest is often reported in terms of merchantable stem volume (Chen et al. 2008, Heath et al. 2010, Stinson et al. 2011). But in reality, forestry companies remove some non-merchantable wood biomass, such as bark and undersize wood (e.g., tops, large branches, and non-merchantable trees), to produce bioenergy or pulp chips (Ride 1999, Heath et al. 2010, Zakrzewski et al. 2011). Thus, the starting point for estimating HWP C is to estimate biomass C in all harvested wood (Figure 2.1, a duplicate of Figure 2 with the highlighted area illustrating the biomass C conversion analyzed in this section). This requires accounting for the amount of bark and undersize wood that is removed from forests with the merchantable wood.

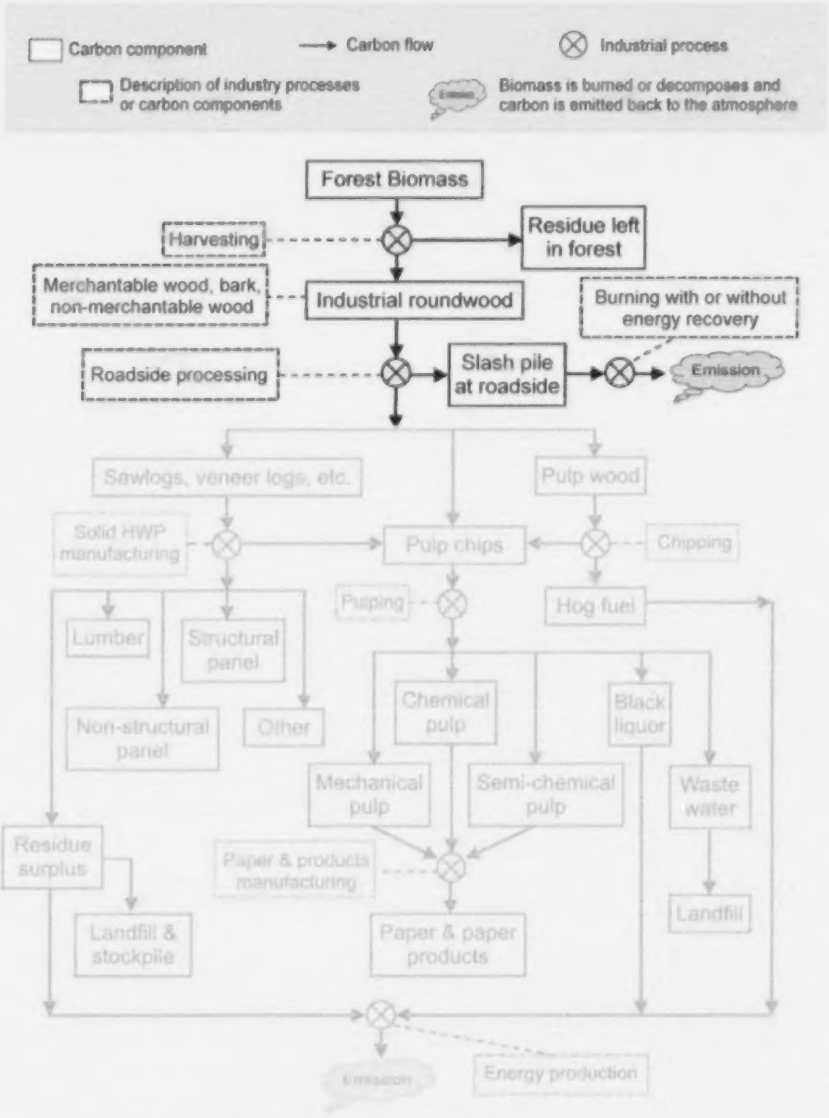

Figure 2.1 *Biomass conversion in forest harvesting.*

In the U.S. national forest C budget model, FORCARB2, from which FORCARB-ON was developed, C in harvested merchantable volume is estimated as the product of merchantable volume, wood specific gravity, and the C fraction of wood. Expansion factors are then used to account for the amount of bark and undersize wood (Smith et al. 2006). In this study, we developed Ontario-specific expansion factors for bark and undersize wood to include in FORCARB-ON.

2.1.1. Bark expansion factors

Table 1 lists the bark expansion factors, defined as the sum of biomass of stem wood and stem bark divided by the biomass of stem wood, developed for Ontario forest types based on published data for Ontario or adjacent jurisdictions (Table A1, Appendix 1). Since we used species groups rather than individual species in our forest C model, FORCARB-ON (Chen et al. 2010), we calculated the arithmetic mean of all factors included in a species group from Table A1 as the bark expansion factor for this species group (Table 1).

For harvest data where species are only differentiated as "softwood" or "hardwood", average bark expansion factors were needed. In Ontario, spruce (*Picea* spp.), jack pine (*Pinus banksiana* Lamb.), and poplar (*Populus* spp.) accounted for almost 87.3% of all wood harvested from 1999 to 2010. Based on the bark expansion factors for these species (Table A1, Appendix 1) and their fractions in harvested wood (tables A2 and A3, Appendix 2), the weighted average bark expansion factors for softwood, hardwood, and all species were estimated as 1.119, 1.189, and 1.138, respectively. In comparison, the bark expansion factors in FORCARB2 for the North Central Forest Region in the United States are 1.181 to 1.185 for softwood and 1.197 to 1.219 for hardwood (Heath et al. 2010). For global forests, the bark expansion factors were estimated by Winjum et al. (1998) as 1.11 and 1.13 for softwood and hardwood, respectively.

In some cases, harvested wood is reported by primary use classes, such as lumber and veneer or pulp and paper. Since the proportion of softwood and hardwood might differ for wood harvested for different primary uses, weighted average bark expansion factors by primary use are provided in Table 2. These were based on wood harvest data for 1999 to 2010 from Ontario and Canada.

Table 1. *Expansion factors used to estimate bark in industrial roundwood for major tree species groups in Ontario (for details about how these were calculated see Table A1).*

Species group	Eastern white Pine	Red pine	Jack pine	Spruce-fir	Aspen-birch	Maple-beech-birch	Softwood	Hardwood
Bark expansion factor	1.133	1.091	1.090	1.137	1.202	1.106	1.119	1.189

Notes: Bark expansion factors for each tree species group were calculated as arithmetic means of all bark expansion factors included in a species group in Table A1. Bark expansion factors for softwood and hardwood were the weighted average of major tree species in Ontario (e.g., spruce, jack pine, and poplar), calculated using individual tree species' bark expansion factors (Table A1) and the fractions of these tree species in harvested wood (Section 2.1.1).

Table 2. *Average bark expansion factors for Ontario and Canada by primary use of harvested wood.*

	Lumber and veneer	Pulp and paper	All harvested wood
Ontario	1.135	1.143	1.138
Canada	1.127	1.158	1.131

Note: Assuming bark expansion factors are 1.119 and 1.189 for softwood and hardwood, respectively. Factors are the weighted average values of softwood and hardwood by their fractions in the total wood volume harvested for a primary use (based on harvest data in 1999-2010).

2.1.2. Undersize tree stem expansion factors

To estimate the total biomass of industrial roundwood (Figure 2), we need to include the undersize trees that are harvested and shipped to mills. Undersize expansion factors are used to convert from merchantable stem wood to industrial roundwood biomass, as defined by Equation 1:

$$F_{undersize} = \frac{V_{roundwood}}{V_{merch_stem}} \quad (1)$$

in which $F_{undersize}$ is the undersize expansion factor, $V_{roundwood}$ the volume of industrial roundwood (the total volume of harvested merchantable stem wood and undersize wood), and V_{merch_stem} the volume of merchantable stem wood. Biomass of industrial roundwood and merchantable stem wood can be used to replace volume in the calculation, assuming volume and biomass of these two components bear the same ratio.

In Ontario, about 3% of the harvested wood delivered to mills is assessed by provincially licensed scalers to determine the volume of undersize wood included (Zakrzewski et al. 2011). We used the harvest volume of merchantable and undersize stem wood to calculate an undersize expansion factor, assuming the volume of harvested wood is proportional to its biomass and C content. Based on scaling data for 2000 to 2011 collected by the OMNR[1], undersize expansion factors varied little among species harvested to produce timber and veneer, with a range of 1.000 to 1.025, averaging 1.014 for all species and 1.014 and 1.011 for softwood and hardwood, respectively.

The expansion factors for wood harvested to produce pulp, paper, and composite panels, calculated using the OMNR data mentioned above, are greater than those for wood harvested to produce lumber and veneer, varying from 1.047 to 1.300. Spruce, jack pine and poplar accounted for 87.3% of the total merchantable volume of the 21 species harvested to produce pulp, paper, and composite panels between 1999 and 2010, with balsam fir (*Abies balsamea* L.), maple (*Acer* spp.), and white birch (*Betula papyrifera* Marsh) accounting for another 10.7%. Thus, we suggest using species-specific undersize expansion factors, or 1.087 and 1.123 for softwood and hardwood, respectively. The merchantable and undersize wood volume harvested, and undersize expansion factors by species harvested for pulp, paper, and composite panel products in Ontario from 2000 to 2011 are summarized in Table 3.

Table 3. *Undersize expansion factors estimated by species using volume of wood (million m³) harvested in Ontario to produce pulp, paper, and composite panels.*

Species	Poplar	Spruce	Jack pine	White birch	Maple	Balsam fir	Others	Softwood	Hardwood	All species
Merchantable volume	36.064	26.317	13.621	3.858	3.037	2.472	1.993	43.775	43.587	87.362
Undersize volume	3.631	2.697	0.916	1.160	0.611	0.117	0.180	3.806	5.505	9.312
Undersize expansion factor[1]	1.098	1.102	1.067	1.300	1.201	1.047	1.090	1.087	1.123	1.107[2]
Combined expansion factor[3]	1.320	1.253	1.163	1.153	1.328	1.190	1.246	1.216	1.335	1.277[2]

Notes: Harvest data (merchantable wood and undersize wood harvested) obtained for 2000 to 2011 from Liisa Raitanen and Mike Naslovar, Provincial Measurement Unit, OMNR (pers. comm., 2012).
[1] Undersize expansion factor calculated as volume of industrial roundwood (merchantable volume plus undersize wood volume) divided by the merchantable volume. [2] Weighted average factors for all species harvested to produce pulp, paper, and composite panels. [3] The definition and calculation of 'combined expansion factors' are discussed in Section 2.1.3; they are included here to avoid additional table with repeated information.

For comparison, we used the fractions of undersize wood in industrial roundwood estimated by Zakrzewski et al. (2011), which was also based on the OMNR scaling data mentioned previously, and calculated the undersize expansion factors for six tree species in northwestern Ontario: red pine (*Pinus resinosa* Ait.) – 1.010, spruce and poplar – 1.190, jack pine and balsam fir – 1.075, and tamarack (*Larix laricina* (Du Roi) K. Koch) – 1.163. Based on the scaling data, spruce, jack pine, balsam fir, red pine, and tamarack accounted for 96.4% of softwood volume harvested to produce HWPs. Thus, it should be reasonably accurate to use the volume proportions of these five softwood species in total softwood harvested and their undersize expansion factors derived from Zakrzewski et al. (2011) to calculate a weighted average undersize expansion factor (1.141). We were unable to produce such a factor for hardwood species, as only that for poplar could be estimated using information from Zakrzewski et al. (2011).

[1] Liisa Raitanen and Mike Naslovar, 2012, Provincial Measurement Unit, Ontario Ministry of Natural Resources, pers. comm.

Undersize expansion factors can be estimated by harvest method, which refers to the form in which wood is delivered to roadside and the primary wood processing that occurs in the forest (e.g., delimbing, bucking). Pulkki[2] summarized harvest methods used by the Canadian forestry sector as (1) full tree (FT), (2) tree length (TL), (3) cut to length (CTL), and (4) multiple log length (MLL). These harvest methods can be described more specifically by considering the roadside processing (e.g., cutting trees into short wood, roadside chipping) and the form of harvested wood shipped to mills (e.g., tree-length roundwood or short wood, pulp chips). According to Pulkki, FT and TL harvesting are widely used in the Canadian forestry sector, while CTL is used mainly in Newfoundland, Nova Scotia, and New Brunswick, and MLL is applied only in British Colombia.

Equation 2 is a modification of Equation 1 that can be used to calculate undersize expansion factors by harvest method.

$$F_{undersize} = \frac{F_{roundwood}}{F_{merch}} \qquad (2)$$

where $F_{undersize}$ is the undersize expansion factor, $F_{roundwood}$ and F_{merch} are the biomass fractions of industrial roundwood and merchantable wood harvested in total aboveground tree biomass, respectively.

Modern harvesting in Canada extracts almost all merchantable wood volume from the forest (Ride 1999). To account for some biomass loss of merchantable stem wood (e.g., wood run over by harvesting machinery), we assumed that 98.0% of merchantable wood biomass is extracted and shipped to mills with the remaining 2% lost in the forest. However, harvest methods vary in the amount of non-merchantable biomass extracted. Ride (1999) estimated that the CTL method extracted 31 and 34% of non-merchantable aboveground biomass during summer and winter, respectively, while these ratios were 13 and 36% for FT-SW method (full tree to roadside and shortwood to mills) (Ride 1999; p. 19-20). These fractions of extracted merchantable stem wood and non-merchantable wood can be used to estimate $F_{roundwood}$ and F_{merch} in Equation 2 if the total aboveground fractions of these two biomass components are known.

Ker (1980) estimated that 67 and 70% of aboveground dry biomass was found in the merchantable stem of softwoods and hardwoods, respectively. In comparison, Jenkins et al. (2003) estimated that merchantable stem wood accounted for 45% of aboveground biomass for softwood species and 50% for hardwood species. But they included trees with a minimum diameter at breast height of 8 cm. Thus, we used the estimates from Ker (1980) to calculate $F_{roundwood}$ and F_{merch} and undersize expansion factors.

Our calculations of undersize expansion factors by harvest method are summarized in Table 4. Using the averages of non-merchantable biomass extraction rates for winter and summer (Ride 1999), percentages of extracted non-merchantable biomass in total aboveground biomass were estimated as 8.13 and 5.45% for softwood and hardwood species, respectively for CTL harvest; these ratios were similarly estimated as 6.13 and 4.11% for FT-SW harvest. Biomass of industrial roundwood is the sum of extracted merchantable stem wood (including bark) and non-merchantable wood. Undersize expansion factors for CTL and FT-SW harvest were calculated as biomass of industrial roundwood divided by the extracted merchantable stem wood and bark (Table 4). The FT-CH (full tree to roadside chips to mill) harvest was estimated as having similar biomass extraction efficiency as CTL harvest (Ride 1999; p. 69, Table 4), and thus we assumed the same undersize expansion factors would apply. Based on Ride (1999; p. 69, Table 4), the FT-TL (full tree to roadside tree length to mill) method resulted in a biomass extraction efficiency between those of the FT-SW and FT-CH harvest methods. Thus, we used the average non-merchantable biomass extraction rates of the latter two to calculate the undersize expansion factor for FT-TL.

The undersize expansion factors developed based on different data and analyses do not vary greatly. In summary, we suggest:

- For wood harvested to produce lumber and veneer, use average undersize expansion factors of 1.104, 1.011, and 1.014 for softwood, hardwood, and all species, respectively.

[2] Available at <www.borealforest.org/world/innova/compare.htm> Accessed Sep. 12, 2012.

- For wood harvested to produce pulp, paper, and composite panels, use species-specific undersize expansion factors (Table 3).
- If harvest method is known, use the harvest-type specific expansion factors (Table 4).

Table 4. *Calculation of undersize expansion factors by harvest method for Ontario (based on Ride 1999).*

	Merchantable stem wood and bark					Non-merchantable			Industrial roundwood[1,6]	Undersize expansion factor[7]	Combined expansion factor[8]
	Stem wood[1,2]	Bark expansion factor	Stem wood and bark[1,3]	Extraction rate (%)	Extracted biomass[1]	Biomass[1,4]	Extraction rate (%)[5]	Extracted biomass[1]			
Cut to length/full tree to roadside chip to mill											
SW	67.0	1.119	75.0	98.0	73.5	25.0	0.325	8.13	81.61	1.110	1.218
HW	70.0	1.189	83.2	98.0	81.6	16.8	0.325	5.45	87.02	1.066	1.243
Full tree to roadside shortwood to mill											
SW	67.0	1.119	75.0	98.0	73.5	25.0	0.245	6.13	79.61	1.083	1.188
HW	70.0	1.189	83.2	98.0	81.6	16.8	0.245	4.11	85.67	1.050	1.224
Full tree to roadside tree length to mill											
SW	67.0	1.119	75.0	98.0	73.5	25.0	0.285	7.13	80.61	1.097	1.203
HW	70.0	1.189	83.2	98.0	81.6	16.8	0.285	4.78	86.34	1.058	1.233

Notes: [1] Values in these columns are fractions of the biomass components in total aboveground tree biomass. [2] Fractions of merchantable stem wood in total aboveground tree biomass for softwood and hardwood were based on Ker (1980). [3] Fraction of merchantable stem wood and bark in total aboveground tree biomass was calculated by multiplying the fraction of merchantable stem wood in total aboveground tree biomass and the associated bark expansion factor. [4] Fractions of non-merchantable wood biomass in total aboveground tree biomass were calculated as the difference of 100% and the fraction of merchantable stem wood and bark. [5] Extraction rates of non-merchantable wood (i.e., tree tops, large branches, and small trees) were based on Ride (1999). [6] Fraction of industrial roundwood in total aboveground biomass is the sum of extracted merchantable stem wood (including bark) and non-merchantable wood. [7] Undersize expansion factors were calculated by dividing values of 'industrial roundwood' with those of 'stem wood and bark'. [8] The definition and calculation of 'combined expansion factors' are discussed in Section 2.1.3; they are included here to avoid repeating the information in a separate table.

2.1.3. Combined expansion factors

A bark expansion factor and its associated undersize expansion factor can be combined into a single expansion factor to directly convert from biomass of harvested merchantable stem wood to biomass of industrial roundwood. A combined expansion factor can be calculated by multiplying a bark expansion factor with its associated undersize expansion factor, or by dividing biomass of industrial roundwood by the amount of merchantable stem wood it contained.

For wood harvested to produce lumber and veneer, the undersize expansion factors were estimated as 1.014, 1.011, and 1.014 for softwood, hardwood and all species, respectively (Section 2.1.2). Since the bark expansion factors were estimated as 1.119, 1.189, and 1.138 for softwood, hardwood, and all species (Section 2.1.1), the combined expansion factors are 1.135, 1.202, and 1.154, respectively. For wood harvested to produce pulp, paper, and composite panels, the combined expansion factors are listed in Table 3; those calculated by harvest method are listed in Table 4.

2.2. Solid harvested wood products

After entering a manufacturing process, the biomass C conversion from harvested tree to finished HWP is determined by three key factors: (1) the division of harvested wood among product types, (2) the production process and its conversion efficiencies, and (3) the amount of mill residue produced and how it is used.

2.2.1. Production of solid harvested wood products in Ontario and Canada

Major solid HWP types include lumber, structural panels (plywood and oriented strand board, or OSB), and non-structural panels (medium-density fibreboard or MDF, hard board, insulating board, and particleboard) (Figure 2.2, a duplicate of Figure 2 with highlighted area illustrating the biomass C conversion during solid HWPs manufacturing). As hardwood lumber accounted for less than 2% of total solid HWPs produced in Canada between 1991 and 2010, we combined it with softwood lumber, and refer to it simply as lumber.

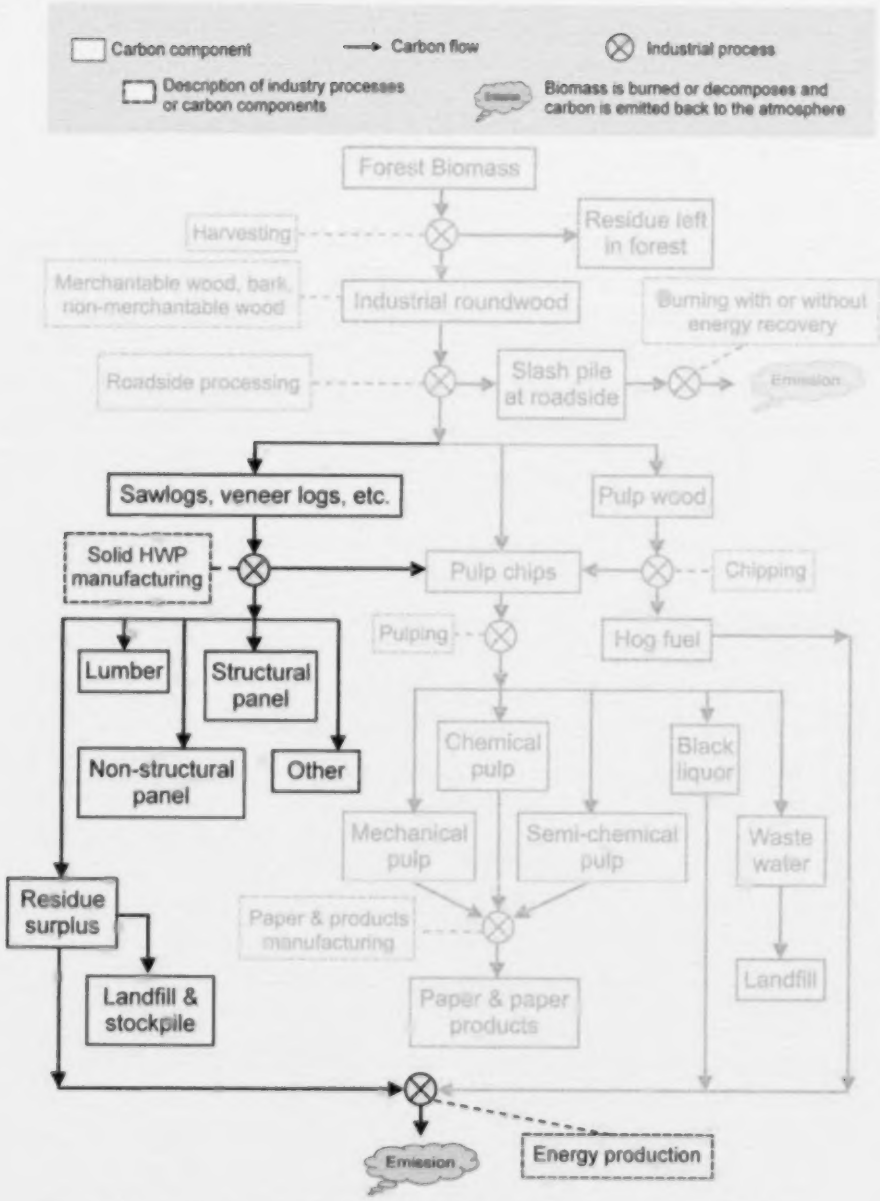

Figure 2.2 *Biomass C conversion during solid harvested wood products manufacturing.*

Production of solid HWPs dropped from a peak in 2002 in Ontario (Table A2, Appendix 2) and in 2004 in Canada (Table A4, Appendix 2). The relative proportion of structural panels generally increased, even though the production of all products fell dramatically over the past decade (tables A2 – A5, Appendix 2). Lumber production accounted for 61.7 to 80.2% of total solid HWPs produced in Ontario (Appendix 2, Table A3) and 74.6 to 89.1% in Canada (Table A5, Appendix 2), dominating the use of harvested wood and biomass C conversion in the forestry sector.

Table 5 lists the average annual production, and average production fractions, of the major solid HWP in Ontario and Canada between 1999 and 2010. Plywood and MDF accounted for less than 6% of the total solid HWPs produced in Ontario and Canada. In Ontario, OSB accounted for a larger fraction of HWPs produced than it did nationally, while particleboard accounted for a smaller fraction.

Though production varied over time, the fractions for all the solid HWP types were relatively stable at both the provincial (Table A3, Appendix 2) and the national (Table A5, Appendix 2) levels. Thus, average production fractions from 1999 to 2010 (Table 5) are likely an appropriate predictor of the amount of solid HWP that will continue to be produced within those jurisdictions.

Table 5. *Average annual production and production fractions (%) of solid harvested wood product (HWP) types for Ontario and Canada from 1999 to 2010.*

Product type		Lumber	Plywood	OSB	MDF	Particleboard	Total solid HWP
Production (thousand m^3)	Ontario	6,302.4	219.2	1,675.3	287.6	317.8	8,02.3
	Canada	71,46.6	2,848.9	6,785.1	1,800.0	10,204.5	93,285.0
Fraction (%)	Ontario	71.6	2.5	19.0	3.3	3.6	100.0
	Canada	76.8	3.1	7.3	1.9	10.9	100.0

Note: OSB – oriented strand board; MDF – medium density fibreboard.

2.2.2. Carbon balance of solid harvested wood products

Biomass C conversion from harvested roundwood to a finished solid HWP is determined by the input-output biomass balance during manufacturing. The biomass balance estimated by Meil et al. (2009) for Canadian HWP industries is presented in Table 6. The balance they reported for lumber production is similar to estimates by Wood and Layzell (2003), who indicated that about 40% of sawlog biomass was converted to lumber, 38% went to pulp chips, and the other 22% remained as processing residue.

We found no published Ontario-specific input-output biomass C balance data. However, because Ontario is one of the main HWP producers in Canada, and Ontario mills were an important data source for Meil et al. (2009), we applied their biomass conversion factors (see Table 6) to Ontario's HWPs.

Table 6. *Biomass balance of solid harvested wood products (HWP) by major product types (from Meil et al. 2009).*

Product type	Source of biomass (%)		Biomass distribution after HWP production (%)					
	Roundwood	Sawmill residue	Product	Pulp chip	Residue	Energy	Stockpile	Landfill
Lumber	100.0		43.1	34.6	21.6[¶]			0.7
Plywood	100.0		49.8	19.4	9.3	18.9	2.6	
OSB	100.0		79.3		2.9	16.3	1.2	0.3
MDF		100.0	88.0			11.0		1.0
Particleboard	8.9	91.1	89.1			10.9		

Notes: Biomass balance values are summarized from Meil et al. (2009). Biomass includes bark on roundwood. OSB – oriented strand board; MDF – medium density fibreboard. Residue: Biomass not contained in the finished HWP or not converted to pulp chips, but can be used to produce wood-based panels or bioenergy. Energy: Biomass burned to produce energy. Stockpile: Biomass waste left in slash piles. Landfill: Biomass waste disposed of in industrial landfills. [¶] No breakdown available for residue from producing lumber or its use to produce wood-based panels or bioenergy.

2.2.3. Estimating wood consumed to produce major types of solid harvested wood products

The consumption of roundwood (including bark and undersized wood) in different HWPs can be estimated using Equation 3:

$$V_i = \frac{Production_i}{Fraction_i} \times Round_{Inp-i} \qquad (3)$$

in which, i – solid HWP type; V_i – wood volume (bark and undersized wood included, m^3), consumed for producing type i HWP; $Production_i$ – production of type i HWP (m^3 from Table 5); $Fraction_i$ – fraction of biomass in the finished type i HWP ('product' column in Table 6); $Round_{Inp-i}$ – percentage of roundwood biomass in input biomass for producing type i HWP ('roundwood' column in Table 6).

Equation 3 was used to estimate wood consumption based on the average annual production of the four major types of solid HWPs produced in Ontario and Canada between 1999 and 2010 (Table 7). Medium density fibreboard was not included in the calculation, as its production does not require industrial roundwood. On average, producing these four HWPs in Ontario and Canada annually consumed 17.2×10^6 and 181.5×10^6 m^3, respectively, of industrial roundwood.

Table 7. *Average annual wood consumed (including merchantable volume, bark, and undersize wood) to produce solid harvested wood products in Ontario and Canada from 1999 to 2010.*

	Industrial roundwood consumption (thousand m^3)				
	Lumber	Plywood	OSB	Particleboard	Total
Ontario	14,622.8	440.2	2,112.6	31.7	17,207.3
Canada	166,233.4	5,720.6	8,556.2	1,019.3	181,529.4
	Percentages of industrial roundwood consumption				
	Lumber	Plywood	OSB	Particleboard	Total
Ontario	84.98	2.56	12.28	0.18	100.00
Canada	91.57	3.15	4.71	0.56	100.00

Note: OSB – oriented strand board; medium density fibreboard is not included as its production does not require industrial roundwood.

2.2.4. Testing combined expansion factors for wood harvested to produce solid harvested wood products in Ontario and Canada

We developed factors for bark expansion, undersize expansion, and both combined to account for the amount of bark attached to harvested merchantable stem wood and undersized trees (sections 2.1.1- 2.1.3). These factors and the roundwood conversion efficiencies provided by Meil et al. (2009) are critical to estimate harvested biomass C and its flows during HWP manufacturing, and would benefit from additional testing.

Between 1999 and 2010, on average, $14,716\times10^3$ m^3 and $149,204\times10^3$ m^3 of merchantable volume was harvested annually in Ontario and Canada, respectively (Table A6; Appendix 3). To test the combined use of the expansion factors and the biomass C balance factors presented by Meil et al. (2009) for solid HWP production, we divided the average annual industrial roundwood consumption (Table 7) by the combined expansion factor for all species for solid HWP production (1.154, Section 2.1.3) to estimate the merchantable volume of harvested wood. Results were $14,911\times10^3$ m^3 and $157,305\times10^3$ m^3 for Ontario and Canada, respectively. These values are reasonably similar to the average annual merchantable volume harvested, indicating the expansion factors and biomass C balance factors suggested by Meil et al. (2009) might be reasonably accurate for Ontario and Canada.

2.2.5. Estimating the amount of solid wood products produced from harvested wood

Average annual production of solid HWPs can be estimated from the average annual volume of merchantable wood harvested as follows:

(a) Expand the merchantable volume of harvested wood to include bark and undersize wood using the combined expansion factors.
(b) Divide the expanded volume among the four major solid HWP types using the wood consumption fractions in Table 5.
(c) Finally, estimate production of the four major solid HWP types using the biomass C balance factors in Table 6.

The production of MDF cannot be estimated using the above method, as it comprises 100% sawmill residue, rather than roundwood. Its production is therefore limited by the availability of sawmill residue. Of the total solid HWPs produced between 1999 and 2010, the average fraction of MDF was 3.6% for Ontario and 1.9% for Canada. These values can be used to estimate future MDF production.

Pulp chips are a by-product of lumber and plywood production, accounting for 34.6 and 19.4% of input volume (including bark) for lumber and plywood production, respectively (Table 6). Thus, pulp chip volume can be estimated from wood used for lumber and plywood, or calculated in a reverse sequence starting from the reported production of lumber and plywood. In both cases, we estimated that between 1999 and 2010, on average, 5.1×10^6 and 58.6×10^6 m^3 of pulp chips were produced annually in Ontario and Canada, respectively, as by-products.

2.2.6. Production and utilization of mill residue from solid harvested wood product manufacturing

Quantifying the biomass and C conversion in solid HWP industries requires estimates not only of the amounts and types of HWPs but also the use and disposal of mill residue. Mill residue has been used to produce energy in HWP production facilities, as raw material to produce particleboard and MDF, disposed of by burning in incinerators, left in stockpiles to decay, used for animal bedding, or disposed of in landfills (Levin et al. 2011).

In Ontario, mill residues used to produce particleboard and MDF were estimated as 16.1 and 16.0% of total residue, respectively (Table 8; BW McCloy & Associates Inc. 2005). For Canada, 5.7 and 2.1% of residues were consumed to produce particleboard and MDF, respectively (Table 8).

Between 1999 and 2010, as a by-product of lumber, plywood, and OSB production, Ontario and Canada respectively produced 3.2×10^6 and 36.7×10^6 m^3 of mill residue each year, estimated based on total wood consumption (Table 7) and biomass balance factors (Table 6). During this period, the average annual production of MDF and particleboard in Ontario were 288×10^3 m^3 and 318×10^3 m^3, respectively, for which 327×10^3 and 325×10^3 m^3, or about 10.0% of annual residue production, was consumed. In the same period, for all of Canada, the average annual production of MDF and particleboard were 1.8×10^6 and 10.2×10^6 m^3, respectively, consuming 2.0×10^6 and 10.4×10^6 m^3, or 5.6 and 28.4% of annual sawmill residue. Since survey data for residue utilization were incomplete (BW McCloy & Associates Inc. 2005), we suggest using residue consumption fractions calculated for this study for particleboard and MDF production, with other residue use fractions adjusted proportionally (the 'adjusted' rows in Table 7). The overall sawmill residue utilization rate was estimated as 94.3 and 83.0% of the production in 2004 for Ontario and Canada, respectively.

The adjusted fraction of residue burned in incinerators without energy recovery is 13.2% of total sawmill residue in Canada. This is mainly in British Columbia and Alberta following increased harvest of mountain pine beetle-infested forests, which offsets the demand for wood residue and at the same time produces more residue as a result of the increased harvest (BW McCloy & Associates Inc 2005). In addition, low energy prices (electricity and natural gas) provide HWP industries less incentive to convert to biomass energy (BW McCloy & Associates Inc. 2005, Bradley 2007).

Table 8. *Sawmill residue utilization in Ontario and Canada in 2004 (fraction of total residue production).*

Ontario	Use type	Cardboard	Landscape	Particle board	MDF	Mill energy	Pellet	Incineration	Stockpile	Landfill
	Fraction[1]	-	0.145	0.161	0.160	0.486	-	0.013	-	0.035
	Adjusted[2]	-	0.171	0.100	0.100	0.572	-	0.016	-	0.041
Canada	Use type	Cardboard	Animal bedding	Particle board	MDF	Mill energy	Pellet	Incineration	Stockpile	Landfill
	Fraction[1]	0.017	0.002	0.057	0.021	0.653	0.031	0.193	0.017	0.008
	Adjusted[2]	0.012	0.002	0.284	0.056	0.476	0.022	0.132	0.011	0.006

Notes: MDF – medium density fibreboard; Mill energy – proportions of residue used internally or externally (e.g., pulp and paper mills) for producing energy. Stockpile – some sawmills leave all or a portion of their residue in stockpiles.

[1] Fraction: Values calculated from survey data of mill residue utilization in Ontario and Canada (BW McCloy & Associates Inc. 2005).

[2] Adjusted fractions recalculated based on production data for particleboard and MDF – (tables A2 and A4, Appendix 2) and the biomass C balance factors reported by Meil et al. (2009) (Table 6). Residue uses for other categories were adjusted proportionally to sum to 1.

2.2.7. Overall wood biomass balance in solid harvested wood product industries

An overall wood biomass balance for solid HWP industries in Ontario and Canada was estimated using data and analysis presented in sub-sections 2.2.1-2.2.4 (Table 9). We assumed 2.5% of all harvested wood biomass is lost as debris by assuming half of all logs are sorted in the forest (5% mass loss as debris when logs are sorted; Dramm et al. 2002). We also assumed another 2.5% of harvested biomass is lost to decomposition and waste during wood transport, storage, and mill yard handling (Pulkki 1991). This 5% biomass loss was counted as emission.

In Ontario, 48.6% of biomass C in logs is converted to solid HWPs, 28.4% to pulp chips, and 13.1% to produce energy (Table 9). For Canadian solid HWP industries, 48.8% of the biomass in logs is converted to lumber and wood-based panel products, 30.9% to pulp chips, and 11.6% is used for energy (Table 9). Similar to Meil et al. (2009), we estimated that an extremely low fraction of processing residue from Canadian solid HWP industries was disposed of in stockpiles and landfills (1.4 and 1.0%, respectively) (Table 9). Of the total biomass harvested to produce solid HWPs in Ontario, 6.9% is not used in a product or to produce energy, compared to 8.6% for Canada overall. These fractions of harvested biomass are either incinerated, stockpiled, placed in landfill, or they decompose.

Table 9. *Overall distribution of industrial roundwood biomass carbon (%) among solid harvested wood product (HWP) types and different residue uses in Ontario and Canada.*

	HWP	Lumber	Plywood	OSB	Particleboard	MDF	Pulp chip
Ontario	Fraction	34.80	1.21	9.25	1.76	1.58	28.40
	Residue use	Energy	Landscape	Incineration[1]	Stockpile	Landfill	Emission[2]
	Fraction	13.07	3.08	0.29	0.20	1.36	5.00
	HWP	Lumber	Plywood	OSB	Particleboard	MDF	Pulp chip
Canada	Fraction	37.50	1.49	3.55	5.33	0.95	30.91
	Residue use	Energy	Animal bedding	Incineration[1]	Stockpile	Landfill	Emission[2]
	Fraction	11.63	0.03	2.53	0.13	0.96	5.00

Notes: The input for solid HWP production is industrial roundwood (bark included), and all the fractions in the table are output components that add to 100%.
OSB: Oriented strandboard; MDF – medium density fibreboard;
[1] Incineration is mill residue burned without energy recovery.
[2] Assuming 5% biomass emission as carbon dioxide due to biomass loss during mill yard handling and storage.

2.3. Pulp and paper

Between 1999 and 2010, the fraction of pulpwood in total wood harvested in Ontario was two times that in Canada's harvest (Table A6, Appendix 3). In addition, about 30% of the forest biomass harvested to produce solid HWPs in Ontario and Canada is also used to produce pulp and paper. The highlighted area in Figure 2.3 illustrates the biomass C conversion in Ontario's and Canada's pulp and paper industries that is analyzed in this section.

2.3.1. Conversion of biomass carbon in debarking and chipping processes

When trees are harvested as pulpwood[3], the biomass is reduced by at least the proportion of the bark during the debarking process (on average 13% of the pulpwood biomass, based on Table 2). Debarking causes an additional 5% average loss of biomass as wood debris (Pulkki 1991). Thus, in total, debarking removes about 18% of pulpwood biomass C.

Chipping of roundwood to prepare it for pulping produces 3% "chip fines" and oversized chips (Pulkki 1991). Chip fines are generally used in hog fuel boilers to produce energy (US EPA 2005), while oversized chips can be sliced to proper chips size and used for pulp (Pulkki 1991). Thus, in addition to the 18% of pulpwood biomass lost to debarking, we assumed 2% of biomass is lost as chipping fines, all of which is used as hog fuel.

Of the 80% of total harvested biomass converted to pulp chips, we assumed an additional 2% decomposes and becomes waste during pulpwood and chip transportation, storage, and mill yard handling (as per Kurz et al. 1992). Thus overall, 78% of harvested pulpwood biomass (bark included) is converted to chips. In comparison, Kurz et al. (1992) estimated that in Canada's pulp and paper industry 80% of pulpwood biomass was converted to pulp chips.

[3] Biomass conversions for pulp chips produced from lumber and plywood production are included in the mass balance calculation for solid HWPs.

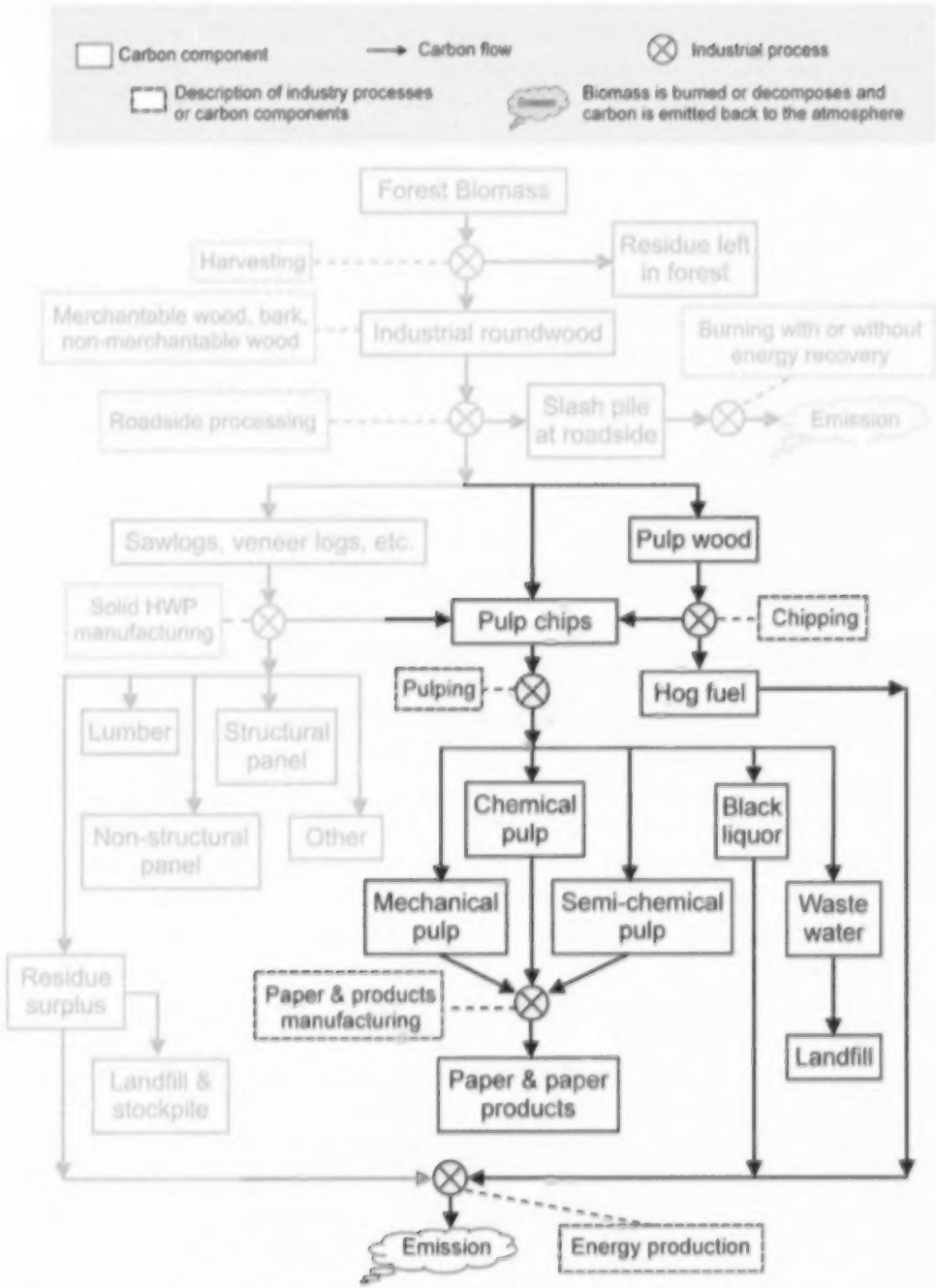

Figure 2.3 *Biomass carbon conversion during the manufacturing of pulp and paper.*

2.3.2. Pulping processes and yield

The main pulping technologies are chemical, mechanical, and semi-chemical. Each of these has different yields (oven dry mass of pulp produced divided by oven dry mass of pulp chips entering the process).

In the United States, pulping yield is within the range of 45 to 50% for bleached chemical pulp, 55 to 85% for semi-chemical pulp, and 85 to 96% for mechanical pulp (US EPA 2005; p.28 Table 4.2). Pulping yields used in this study were based on those suggested by Pokhrel and Viraraghavan (2004) for Canada's pulp industry: 45% for chemical pulp, 92.5% for mechanical pulp, and 87.5% for semi-chemical pulp. Due to the lack of Ontario-specific data, we assumed that their estimates also apply to Ontario's pulp industry.

2.3.3. Production of pulp, paper, and paper products in Ontario and Canada

Based on available information, we made the following assumptions about the types of pulp used in major paper products:

(a) Printing, writing, and household/sanitary paper are made from chemical pulp.
(b) Newsprint is made from mechanical pulp.
(c) Half of the wrapping/packaging/paperboard products are made from chemical pulp, and the other half from mechanical pulp.
(d) Semi-chemical pulp is commonly used to manufacture corrugated cardboard[4].

The production of market pulp[5] and paper and paper products in Ontario from 1999 to 2010 is summarized in Tables A7 and A8 (Appendix 4), respectively. Table 10 presents an overview of pulp production by pulping processes, in which paper and paper products are converted to pulp products using the assumptions (a) to (d) listed above and then combined with market pulp.

Canada's annual production of market pulp and paper and paper products are presented in Tables A9 and A10 (Appendix 4), respectively. From these we summarized the overall annual pulp production in Canada between 1999 and 2010 (Table 11). Market pulp production was estimated as described above for Ontario, but here sulphate and sulphite pulp accounted for 96 and 4% of total chemical pulp, respectively; for simplicity these were combined as chemical pulp. From 2001 to 2010, on average, chemical, mechanical, and semi-chemical pulp accounted for 51.3, 46.5, and 2.2% of Canadian pulp production, respectively.

Table 10. *Overall pulp production in Ontario from 1999 to 2010; paper and paper products (for details see Table A8, Appendix 4) were converted to pulp production by pulping processes using assumptions (a) to (d) (Section 2.3.3), and then combined with market pulp production (Table A7, Appendix 4)*

Year	Production (thousand ODT[1])	
	Chemical	Mechanical
1999	2,227.7	2,361.5
2000	1,865.8	2,937.7
2001	2,137.3	2,578.7
2002	2,688.4	2,853.3
2003	2,585.5	2,798.2
2004	3,528.2	2,756.1
2005	1,913.8	2,255.3
2006	1,630.4	1,553.8
2007	1,312.1	1,336.4
2008	1,089.8	982.1
2009	565.6	726.8
2010	475.0	915.6
Average	1,835.0	2,004.6
Fraction[2]	46.25	53.75

[1] Available from <www.nfdp.ccfm.org/products/jurisdictional_e.php> Accessed Sept. 15, 2012.
[2] Market pulp is pulp sold to markets outside Ontario.

Table 11. *Overall pulp production in Canada from 1991 to 2010 (thousand ODT[1]); paper and paper products (Table A8, Appendix 4) were converted to pulp production by pulping processes using assumptions (a) to (d) (Section 2.3.3), and then combined with market pulp production (Table A9, Appendix 4).*

Product type	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Chemical[2]	16,793.4	16,771.8	17,227.2	19,002.9	19,663.7	19,341.1	19,732.9	19,629.4	20,958.1	21,784.6	21,039.5
Mechanical	20,295.5	19,900.3	20,523.1	21,220.5	21,615.0	21,023.6	21,590.0	20,271.4	21,669.8	22,694.5	20,939.0
Semi-chemical	567.0	459.9	390.6	335.7	320.4	342.9	363.6	433.8	495.9	505.8	454.5
Product type	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Average**	**Fraction**
Chemical[2]	21,590.8	21,634.3	22,347.3	21,190.3	19,525.9	19,001.0	17,223.6	14,593.3	14,868.0	19,196.0	0.485
Mechanical	21,200.9	21,410.2	21,362.6	20,719.5	19,447.7	18,182.2	16,571.7	13,320.9	14,262.1	19,911.0	0.503
Semi-chemical	468.0	503.1	532.8	484.2	429.3	443.7	439.2	413.1	402.3	439.3	0.012

Notes: [1] Converted from air-dry tonne (i.e., 10% moisture content) used in the FAO database to oven-dry tonne (ODT, i.e., 0% moisture).
[2] Chemical pulp includes bleached and unbleached sulphate and sulphite pulp and dissolving pulp.

2.3.4. Dividing pulp chips among pulping processes

To use the pulping yields from the three major pulping processes, as summarized in sub-section 2.3.2, to estimate pulp production, we need to divide pulp chips among pulping processes. We assumed that each 100 tonnes of pulp produced in Ontario is divided 46.3:53.7 chemical:mechanical, based on the production fractions in Table 10. The yield factors summarized in Section 2.3.2 allow us to estimate the amount of chips required to produce these amounts of pulp. From this, the fractions of pulp chips consumed by each pulping process can be estimated (Table 12). Similar calculations were done for Canada's pulp and paper industries (Table 12).

About 78% of pulpwood (bark included) can be converted into pulp chips (Section 2.3.1). These chips, together with those from lumber and plywood production, were divided among the major pulping processes using parameters given in Table 12. Pulp productions could then be estimated from pulp chips divided among pulping processes using the pulping yield factors summarized in Section 2.3.2.

Table 12. *Quantity of pulp chips used to produce each 100 ODT[1] of pulp.*

	Pulp type	Production[2] (ODT)	Yield	Pulp chip (ODT)	Chip fraction (%)
Ontario	Chemical	46.3	0.450	102.8	63.9
	Mechanical	53.7	0.925	58.1	36.1
Canada	Chemical	48.5	0.450	115.9	65.9
	Mechanical	50.3	0.925	49.5	33.3
	Semi-chemical	1.2	0.875	2.3	0.8

Notes: [1] ODT: oven-dry tonne, i.e., 0% moisture content.
[2] The production by pulp type is calculated using the fraction of each type of pulp in total production (see Table 10 for Ontario and Table 11 for Canada).

2.3.5. Testing the combined expansion factors to estimate pulpwood biomass carbon and pulp chip and pulp production

We tested the combined use of expansion factors estimated for pulpwood and other factors that determine the production of pulp chips and pulp. Because pulp, paper, and paper product production decreased dramatically in Ontario and Canada from 2005 to 2010, the fractions of input fibre from pulpwood, pulp chips stemming from lumber production, and recycled paper may be changing. Thus, we used production data for 1999 to 2005 when HWP production was relatively stable. Average annual chemical and mechanical pulp production in Ontario during this period were 2.4 million and 2.6 million oven-dry tonne (ODT, i.e., 0% moisture content), respectively, requiring a total 8.2 million ODT of pulp chips or fibre from recycled paper (estimated using pulping yields). For the same period, the average annual pulpwood harvest, 6.4 million m^3 (Table A6, Appendix 3) was multiplied by the combined expansion factor of 1.143 (Table 2) to include bark and harvested undersize wood, resulting in 7.3 million m^3 of industrial roundwood volume. From the industrial roundwood, 5.7 million m^3 (78% of industrial roundwood) or 2.9 million ODT of pulp chips was produced (assuming 0.5 tonne dry mass per 1 m^3 of wood). As well, during the

same period, the average annual lumber and plywood production were 7.4 million m^3 and 0.3 million m^3, producing 6.1 million m^3 or 3.0 million ODT of pulp chips. The difference in the amount of pulp chips required and the total production from the two sources, i.e., 2.3 million ODT, represents the average annual consumption of recycled paper by Ontario's pulp and paper industries, which accounted for 28% of the total required input fibre for overall pulp production in the province.

The same calculations were made for Canada's pulp and paper products using production data from 1999 to 2005. The overall average annual production in Canada was 21.5 million ODT, 21.4 million ODT, and 0.5 million ODT for chemical, mechanical, and semi-chemical pulp, respectively (Table 11), requiring a total of 71.5 million ODT of pulp chips or recycled paper. The average annual pulpwood harvest was 26.2 million m^3 (in merchantable volume), from which 11.9 million ODT of pulp chips were produced. Meanwhile, lumber and plywood production, 78.7 million ODT and 2.9 million ODT per year, respectively, was estimated to produce 32.2 million ODT of pulp chips. The difference in the required annual input of wood fibre and the amount of pulp chips produced from the two sources, i.e., 27.5 million ODT (38.5% of total fibre input), was assumed to be the amount of recycled paper and paper products used in Canada's pulp and paper production.

The ratio of recycled paper we estimated for Ontario is similar to that estimated by FPAC (2012), i.e., 28%, while our national level estimate was about 10% higher. However, we still consider the combined use of all expansion factors developed or summarized as part of this study to estimate the production of pulp and paper products in Ontario and Canada as reasonably accurate given the complexity involved in producing pulp, paper, and paper products, as well as the assumptions involved in our estimates.

2.3.6. Use of hog fuel to produce energy

About 8% of industrial energy fuel use in Canada is biomass, and almost all of this biomass energy is consumed by the pulp and paper industry to replace natural gas (National Energy Board 2010). BW McCloy & Associates Inc. (2005) suggested that Canadian pulp mills typically purchase additional wood residue to produce bioenergy. As demand for biomass for bioenergy and other value-added HWPs is increasing, residue from HWP industries is almost completely committed (BW McCloy & Associates Inc. 2005).

In Ontario, total mill residue production was estimated as 2.6 Mt in 2004, of which only 0.12 Mt was not used (i.e., burned without energy recovery, or disposed of in stockpiles or landfills) (BW McCloy & Associates Inc. 2005). Levin et al. (2011) reported similar results for wood residue produced and used from sawmills in eastern Ontario.

We assumed that, on average, 95% of hog fuel produced by pulp mills in Ontario and Canada as a whole is used internally for energy production, with the remaining 5% lost to decomposition and waste during transport and mill yard handling (and therefore counted as an emission).

2.3.7. Production and treatment of waste biomass from pulping

The amount of waste biomass produced by the pulp industry varies depending on the pulping technologies. For mechanical pulping, 95% of chip biomass is converted to pulp, with most of the remaining 5% ending up as wood fibres in liquid effluent (Thompson et al. 2001). These fibres are diluted in large volumes of water and cannot be used to generate energy so are disposed of in landfills. Similarly for semi-chemical pulping, 85% of chip biomass is converted to pulp and the remaining 15% is assumed disposed of in landfills.

For chemical pulping, on average only 45% of biomass in pulp chips is converted to finished pulp. Most of the remaining 55% chip biomass is contained in the lignin-rich black liquor, which is burned to produce heat and power at mills (Thompson et al. 2001; AMEC Forest Industry Consulting 2002, p.32). According to Bonsor et al. (1988), sulphate mills in Ontario recovered and burned for energy 96 to 99.5% of the black liquor they produced; the rest was disposed with mill effluent. Thus, for chemical pulping in Ontario and Canada, we use the lower limit (96%) as the energy recovery rate from black liquor; the remaining 4% is assumed to be disposed of in landfills.

2.4. A summary of biomass carbon conversion for Ontario's and Canada's forestry sector

2.4.1. Conversion of biomass carbon of industrial roundwood during the transition to harvested wood product

The potential contribution to climate change mitigation from the forestry sector in Ontario and Canada can be assessed based on the amount of biomass C converted when HWPs are produced and the associated C stocks and emissions (Figures 1 and 2). Between 1999 and 2010, on average, sawlog harvesting accounted for 71.8% of the total merchantable volume harvested in Ontario and pulpwood accounted for the remaining 28.2% (Table 12). In Canada as a whole, logs and pulpwood accounted for 85.7 and 14.3%, respectively, of the total merchantable volume harvested (Appendix 3, Table A6).

Figure 3 and Table 13 illustrate biomass C conversion of harvested industrial roundwood to HWPs in Ontario and Canada. On average, 61.3 and 64.6% of total biomass C harvested in Ontario and Canada, respectively, were estimated to be contained in various types of HWPs immediately after manufacturing. Biomass burned for energy was estimated to account for 29.3 and 26.2% of total biomass harvest in Ontario and Canada, respectively. Overall, about 9% of total harvested biomass was lost through decomposition, combustion without energy recovery, or disposal in landfills.

Table 13. *Distribution of harvested biomass carbon among harvested wood product types and the different uses of mill residue immediately after product manufacturing (numbers may not add to 100% due to rounding).*

Category	Biomass C (%)	
	Ontario	Canada
Total in use	61.3	64.6
Lumber	25.0	32.1
Structural panel[1]	7.5	4.3
Non-structural panel[2]	2.4	5.4
Pulp	26.4	22.8
Stockpile	2.4	0.1
Landfill	2.7	2.3
Combustion for energy	29.3	26.2
Total emission	4.4	6.8
Non-energy combustion	0.2	2.2
Decomposition	4.2	4.6

Notes: [1] Structural panels include plywood and oriented strand board.
[2] Nonstructural panels include particleboard, medium density fibreboard, hardboard, and insulating board.

2.4.2. Production trends in Ontario and Canada and their implications for estimating the production of harvested wood products

Figure 4 illustrates production trends for Ontario and Canada's industrial roundwood and major HWP types (chemical pulp, mechanical pulp, lumber, structural panels, and non-structural panels). As expected, the production of lumber and pulp at both the provincial and national levels and the production of panels from Ontario were directly correlated with changes in industrial roundwood harvest. This indicates that production of these HWPs can be accurately estimated as fractions of industrial roundwood harvest (Figures 3a, b).

At the national level (Figure 4b), the production of structural and non-structural panels increased significantly from 1991 to 2004, while industrial roundwood harvest only increased slightly. This indicates the increased use of wood residue from lumber and veneer production to make wood-based panels.

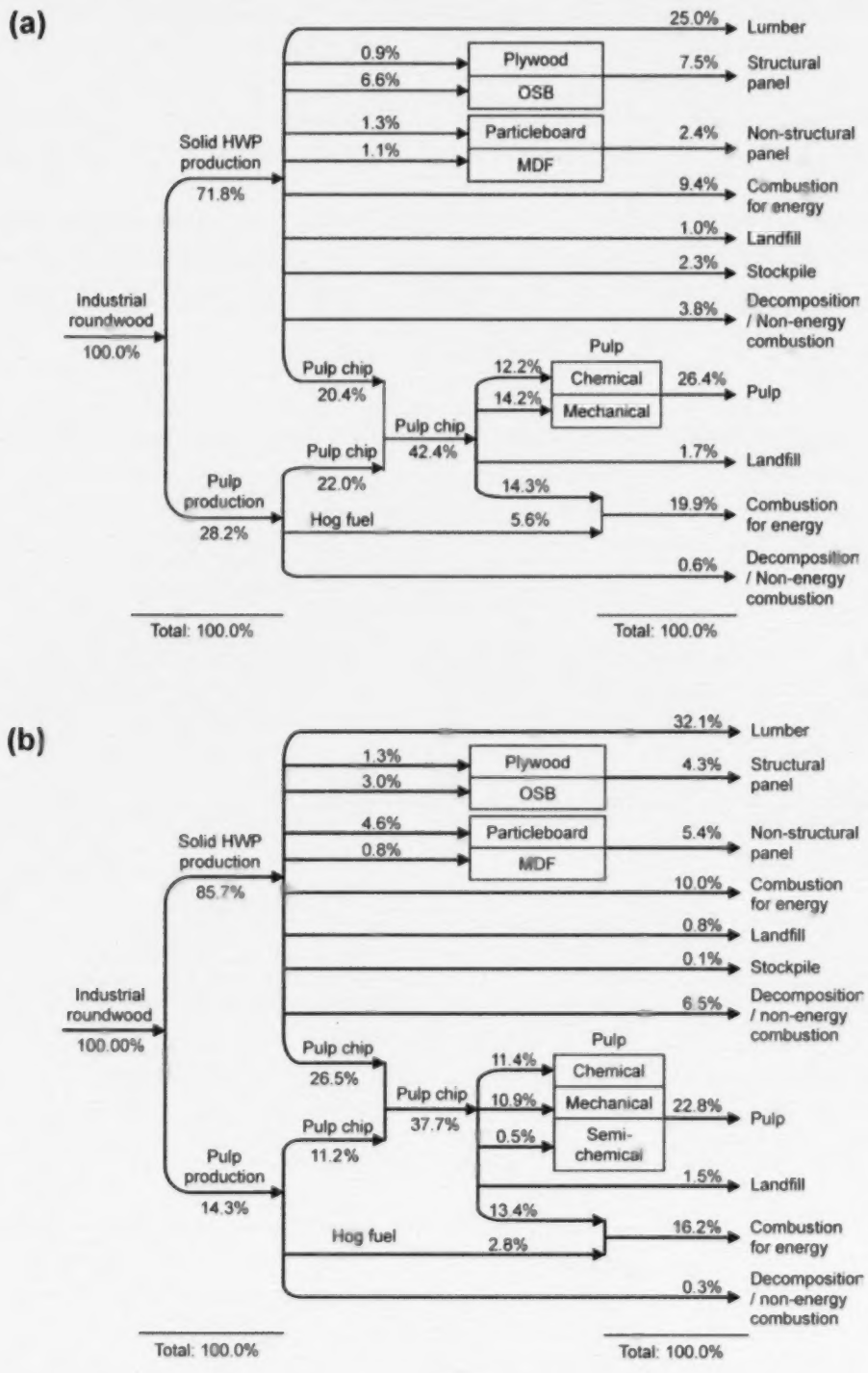

Figure 3. *Biomass carbon conversion in (a) Ontario's and (b) Canada's forestry sector. Notes: Assuming the production of HWPs is completed within the year of harvest (OSB – oriented strandboard; MDF – medium density fibreboard, but is actually a combination of MDF, hardboard, and insulating board). Numbers may not add to 100 due to rounding. Bark and sub-merchantable wood harvested to product pulp are included.*

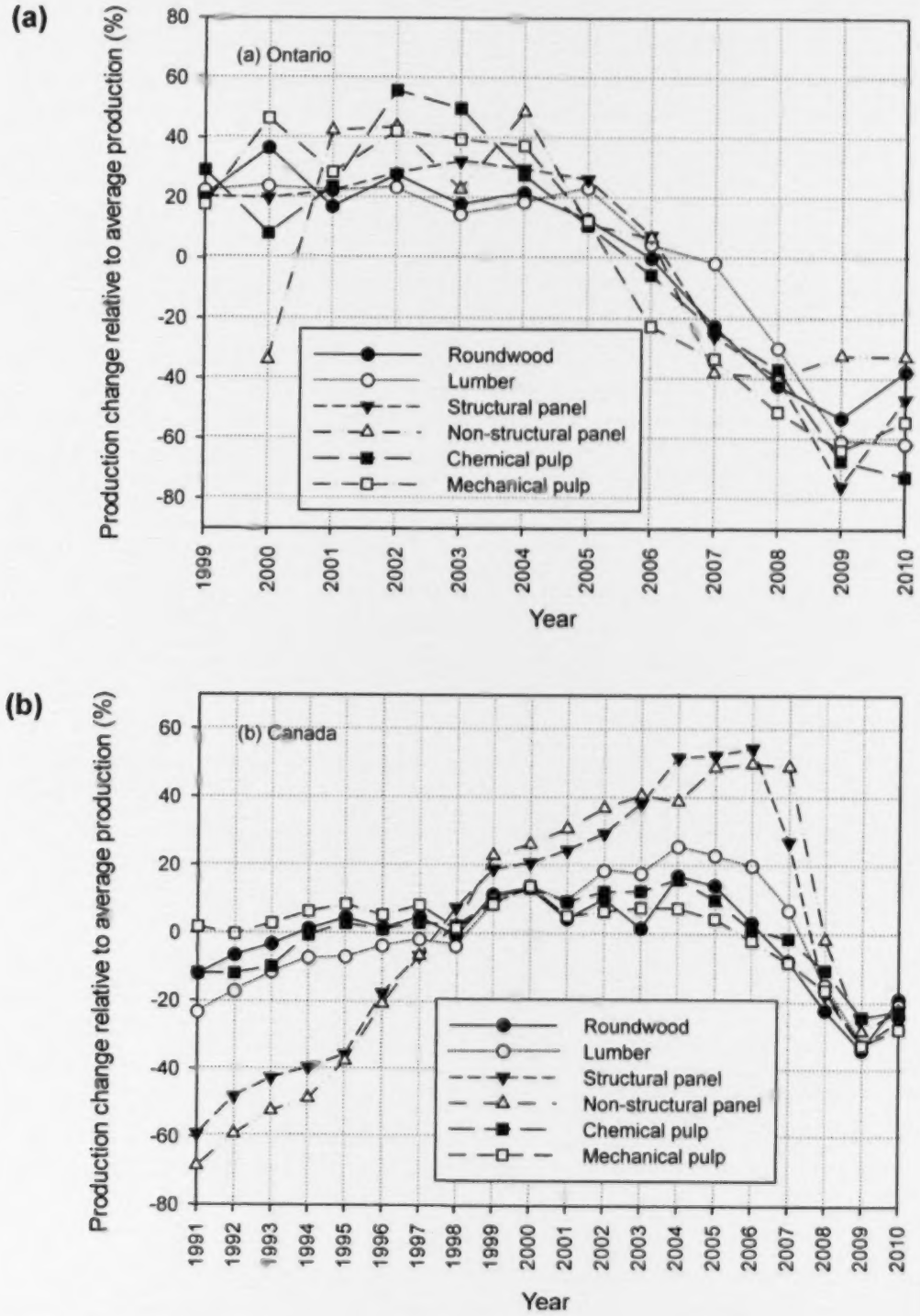

Figure 4. *Production change (%) relative to average annual production of industrial roundwood and harvested wood products (HWPs): (a) in Ontario from 1999 to 2010 and (b) in Canada from 1991 to 2010.*

3. End-use analysis – fate of Ontario's and Canada's harvested wood products

As shown in Figure 1, the second major life stage of HWPs occurs when they are placed and remain in a primary end use. To determine the C stocks of HWPs in use, three important factors need to be considered: types of end uses, the fraction of HWPs in each end use, and the service lives associated with these end uses.

Historically, Canada has been one of the largest HWP exporters in the world, accounting for one sixth of global exports (CCFM 2006). Each end use country may differ in the way it uses HWPs. Thus, to estimate C stocks of HWPs in use for Ontario and Canada, both domestically consumed and exported HWPs must be accounted for.

3.1. Canada[6]

3.1.1. Export of solid harvested wood products

Canadian HWP industries export most of their products to foreign markets. From 2005 to 2010, the fraction of solid HWPs exported decreased from 78.6 to 55.8%, with an average export fraction of 63.7 (Table A11, Appendix 5). Likewise, lumber exports have fallen as a fraction of total Canadian HWP production, from a high of 75.7% during 1993 to 1998 to 58.4% from 2007 to 2010. On average in 2005 to 2010, 82.9% of Canadian OSB was exported, but its export fraction decreased as well (FPInnovations 2009, 2011). The same decreasing trend in export fraction is seen for all major Canadian solid HWPs, probably due to decreasing housing starts in the United States (FPInnovations 2009). Table A12 (Appendix 5) shows the Canadian solid HWP consumed by the United States from 2005 to 2010, illustrating this decrease.

In summary, 63.7% of Canada's solid HWPs were exported, of which 86.1% (or 54.8% of total Canadian production) was consumed by the U.S. market. Thus, the United States and Canada combined consumed 91.1% of the solid HWPs produced in Canada.

3.1.2. Export of pulp, paper, and paper products

Table A13 (Appendix 5) shows the fractions of Canadian pulp and paper products exported, calculated based on production and export data. Canadian chemical pulp is largely exported, while most mechanical pulp is used domestically. However, the domestically consumed pulp is converted to paper and paper products by Canadian paper mills, and mostly shipped to foreign markets (Table A13, Appendix 5). Thus, from 1991-2010, the overall average export fraction for Canadian pulp and paper products was 85.9%.

Table A14 (Appendix 5) summarizes the consumption fractions of Canadian pulp and paper products by major importers (FPInnovations 2009, 2011). The United States was the primary importer, consuming 62.6% of all exported Canadian pulp and paper products (53.8% of total Canadian production). Together, the United States and Canada consumed 67.9% of all pulp, paper, and paper products produced in Canada. Practices and policies for use and disposal of these products in the United States and Canada are therefore important considerations when quantifying C stocks and emissions for Canadian pulp and paper products.

3.1.3. End uses of Canadian solid harvested wood products

Construction is the largest user of solid HWPs in the United States, consuming 67.0% of lumber, 81.0% of structural panels, and 43.0% of non-structural panels (Table 14; McKeever 2009). In total, residential construction in the United States and Canada consumes about 40% of Canada's lumber (Statistics Canada 2002). The estimated fractions of lumber used in construction in the United States in 2006 was similar to the 70% estimate by Kurz et al. (1992) for Canadian lumber as a whole.

In comparison, Canadian residential construction consumed 53.5% of softwood lumber (Table 15; Spelter et al. 2009). We estimated that lumber consumed in non-residential construction was 10% of the lumber used in residential construction, based on an estimate by O'Connor (2004).

[6] Some of the national level information is needed to produce provincial level analysis, and is thus presented first in this section.

Adair and McKeever (2009) suggested the rates of wood use in construction in the United States and Canada are similar. Thus, to obtain Canadian rates of structural and non-structural panel use relative to that of lumber (Table 15), we used the ratios from Table 14 for U.S. construction.

Table 14. *Fractions of solid harvested wood products in different end-uses in the United States in 2006 (McKeever 2009).*

Use of solid HWP	Lumber	Structural panel	Non-structural panel
Total construction	0.670	0.810	0.430
New residential sub-total	0.337	0.452	0.222
Single-family house	0.293	0.393	0.193
Multi-family house	0.027	0.036	0.018
Mobile home	0.017	0.023	0.011
Residential repair and remodel	0.261	0.246	0.148
Non-residential	0.073	0.112	0.060
Manufacturing use[1]	0.080	0.110	0.480
Shipping and packaging	0.120	0.020	
Other[2]	0.130	0.060	0.090

Notes: [1] Manufacturing use – Solid HWP used by manufacturing industries as raw materials, or as wood jigs, models, patterns, flasks, etc. Shipping and packaging – 90% of lumber and 70% of structural panels are used as pallets, the rest are used for purposes such as blocking and bracing in transportation of products from manufacturing industries. [2] Other – includes improvement of non-residential construction, roof supports in mines, rail ties, rail cars, household and commercial furniture, etc.

Table 15. *Fraction of solid harvested wood products in different end-uses in Canada.*

End use	Lumber	Structural panel[2]	Non-structural panel[2]
Construction sub-total	0.589	0.674	0.368
New residential sub-total	0.217	0.291	0.143
Single-family house	0.171	0.229	0.113
Multi-family house	0.046	0.061	0.031
Residential repair and remodel	0.318	0.300	0.181
Non-residential	0.054[1]	0.083	0.044
Other	0.411	0.326	0.632

Notes: Data sources: Average end-use lumber consumption from 2003 to 2009 obtained from Spelter et al. (2009). [1] Non-residential construction consumption was estimated as 10% of the consumption of residential construction based on O'Connor (2004). [2] Proportions of structural and non-structural panel used in Canadian construction for lumber, structural panels, and non-structural panels were those used in the United States (Table 18) as Canadian data were not available.

3.1.4. An overall end use matrix for Canadian-made solid harvested wood products

Using the production and export data summarized for 2005 to 2010, we estimated that 91.1% of Canadian solid HWPs were consumed by the United States and Canada (Section 3.1.1). For simplicity, we assumed that the remaining 8.8% of Canadian solid HWPs shipped to other countries were used similarly, and proportionally divided the remaining 8.8% between the latter two countries based on their consumption of Canadian solid HWPs. The simplified fractions consumed in the United States and Canada were divided among the major end-uses using factors in Tables 14 and 15, and the results were combined to produce the overall end use matrix for Canada's solid HWPs (Table 16).

Table 16. *Combined fractions of solid harvested wood products in different end-uses in domestic and international markets.*

End use	Lumber	Structural panel	Non-structural panel	All solid HWPs
Construction total	0.637	0.768	0.410	0.621
New residential sub-total	0.287	0.402	0.197	0.288
Single-family house	0.243	0.342	0.167	0.243
Multi-family house	0.035	0.044	0.022	0.034
Mobile home	0.010	0.016	0.007	0.010
Residential repair and remodel	0.284	0.263	0.159	0.266
Non-residential construction	0.065	0.103	0.055	0.067
Other[1]	0.363	0.232	0.590	0.379

Note: [1] All other uses accounts for all non-construction use of Canadian solid HWP, e.g., in manufacturing, shipping, and packaging.

3.1.5. Paper and paper product mix for Canada's pulp and paper

Different paper and paper products can have unique end uses that determine their service lives and disposal (Skog and Nicholson 2000), as well as different rates of decomposition once they are in landfills (Barlaz 2004). To produce an overall paper and paper product mix for the entire Canadian pulp and paper industry, the market pulp needs to be converted to paper and paper products and added to the amount of Canadian paper and paper products produced.

From 2005 to 2010, most Canadian chemical pulp was exported (Table A13, Appendix 5). Of the total exports, 42.9, 40.2, and 11.0% were consumed by the United States, major Asian economies (Japan, China, India, Indonesia, etc.) and the EU27, respectively (Table A14, Appendix 5). To simplify the estimation of paper and paper products produced from exported chemical pulp, we assumed these countries consumed all of it.

Based on the production of paper and paper products by these major consumers (FAOSTAT database[7]) of Canadian market chemical pulp and assumptions (a) to (d) about the use of chemical pulp to produce paper and paper products (Section 2.3.3), we estimated that, on average, 11.1, 43.3, 42.6, and 3.0% of the exported Canadian chemical pulp was converted to household and sanitary paper, printing and writing paper, wrapping and packaging paper and paperboard, and other paper and paper products, respectively. Using these fractions, average annual production of paper and paper products from 2001 to 2010 could be estimated using the annual chemical pulp exports of 7.9 million ODT. To produce an overall paper and paper product mix for the Canadian pulp and paper industry, paper and paper product production estimated for exported Canadian chemical pulp were added to the domestic paper and paper product production (Table 17).

Table 17. *Overall paper and paper product mix for Canadian pulp and paper industries.*

Product type	Fraction of total production
Newsprint	0.309
Printing and writing paper	0.335
Wrapping and packaging paper and paperboard	0.279
Household and sanitary paper and other paper and paperboard	0.077

3.2. Ontario

3.2.1. Export of solid harvested wood products

According to the Ontario Forest Industries Association[8], 70% of Ontario's HWPs were exported in 2005, but this decreased to 40% by 2009. In 2010, 94.0% of the exported Ontario HWPs were shipped to the United States[9]. Between 1999 and 2010, on average, the United States consumed 96.3% of the HWPs exported from Ontario. As there was a lack of more specific data, we assumed the export fractions were the same for Ontario's solid HWPs and pulp, paper, and paper products as a whole.

Assuming export fractions decreased linearly from 70% in 2005 to 40% in 2010, the average export fraction for Ontario's solid HWPs during this period was estimated as 56.8%. We assumed exports prior to 2005 were a constant fraction of total production (70.0%). Thus, from 1991 to 2010, 37.5% of Ontario solid HWP was consumed in Canada and of the 62.5% exported, the United States consumed on average 60.2%. Thus together, the United States and Canada were estimated to consume about 97.7% of Ontario's solid HWPs. For simplicity, we assigned the remaining 2.3% of Ontario's solid HWP exports proportionally to the United States and Canada, raising their average consumption for the period 1991 to 2010 to 61.6 and 38.4%, respectively.

[7] National production data available at <http://faostat.fao.org/site/626/default.aspx#ancor>. Accessed October 10, 2012.

[8] Available at <www.ofia.com/files/POYRY%20Summary%20Report.pdf>. Accessed July 30, 2012.

[9] Calculated from the monetary value of exported Ontario solid HWPs available at <http://cfs.nrcan.gc.ca/statsprofile>. Accessed July 30, 2012.

The 61.6% of Ontario's solid HWPs consumed by the United States can be approximately divided into major end uses based on values provided in Table 14. The 38.4% of Ontario's solid HWPs consumed domestically was similarly divided among the major end-uses in Canada (Table 15). An overall end-use matrix for Ontario's solid HWPs was produced by summing the end-use percentages calculated as described above for solid HWPs consumed domestically and by the United States (Table 18).

Table 18. *Fractions of Ontario's solid harvested wood products (HWPs) in different end-uses in domestic and international markets.*

Use	Lumber	Structural	Non-structural	All solid HWPs
Construction sub-total	0.639	0.758	0.406	0.648
New residential sub-total	0.291	0.39	0.192	0.305
Single-family house	0.246	0.33	0.162	0.258
Multi-family house	0.034	0.046	0.023	0.036
Mobile home	0.011	0.014	0.007	0.011
Residential repair and remodel	0.283	0.267	0.161	0.271
Non-residential construction	0.065	0.101	0.053	0.072
Other	0.361	0.242	0.594	0.352

3.2.2. Paper and paper product mix

A very small fraction of Canada's mechanical pulp was exported (Table A13, Appendix 5), which we assumed was also true for Ontario. Therefore, for simplicity we assumed that the average annual production of 0.5 million ODT of Ontario's market mechanical pulp from 1999 to 2010 (Table 16) was consumed entirely by Canadian domestic markets. In comparison, 61.6% of Ontario's 1.1 million ODT average annual production of market chemical pulp (Table 16) was exported to the United States, with the remainder consumed domestically (Section 3.2.1).

We converted the exported and domestically consumed market pulp to paper and paper products using U.S. and Canadian paper and paper product mixes (see Section 3.1.5). In conjunction with Ontario's production of paper and paper products, we estimated the overall paper and paper product mix for Ontario's pulp and paper industries as a whole (Table 19).

Table 19. *Overall paper and paper product matrix for Ontario's pulp, paper, and paper products industries.*

Product type	Fraction of total production
Newsprint	0.331
Printing and writing paper	0.320
Wrapping and packaging paper and paperboard	0.277
Household and sanitary paper and other paper and paperboard	0.720

3.3. Estimating carbon stocks of in-use harvested wood products produced in Canada

3.3.1. Service life of Canada's HWPs

Service-life of a HWP is the length of time (often years) it remains in its original end use. Half-life ($t_{1/2}$), which is the number of years it takes to lose one-half of the initial material of a HWP from its original end-use (Skog 2008), is often used to define the service life of a HWP. Half-life for construction lumber ranges from 60 to 100 years, and for paper and paper products from 1 to 6 years (Kurz et al. 1992, UNFCCC 2003, US EPA 2007). Table 20 summarizes half-life estimates by HWP end use in the United States based on information presented by Skog (2008) and US DOE (2006).

The United States consumed most of Canada's HWPs, including those from Ontario. Together, the United States and Canada consumed 91.1% of Canadian solid HWPs (Section 3.1.1), 85.9% of pulp and paper products (Section 3.1.2), and 97.5% of Ontario's HWPs (Section 3.2.1). Since Canadian data on HWP half-life is lacking, we relied on and applied statistics for HWPs used in the United States to Canada.

Table 20. *Half-lives (years) for harvested wood products by end uses (US DOE 2006, Skog 2008).*

End use half life (years)				
Single family house	Multi-family house	Residential repair and remodelling	Other	Paper
85	50	25	20	2.5

3.3.2. Carbon stocks of in-use harvested wood products

Carbon in HWPs is roughly half of the product's dry weight (IPCC 2006, Table 12.4, p. 12.19). The C stock of HWP in use can be estimated using a first-order decay model described by Equation (4) (IPCC 2006, Pingoud and Wagner 2006):

$$C(t+1) = e^{-k} \times C(t) + \frac{1-e^{-k}}{k} \times I(t) \qquad (4)$$

where:

t = year

$C(t)$ = the C stock of the HWP in use at the beginning of year t. The product of $C(t)$ and e^{-k} describes C in HWPs retained in use from year t to year $t+1$.

k = the constant annual rate at which the HWP placed in an end use goes out of use; calculated as

$k = \ln(2) / t_{1/2}$ where $t_{1/2}$ is the half-life of the HWP in a particular end-use.

$I(t)$ = the inflow of the HWP C to the particular end use in year t, made from newly harvested wood or recycled HWPs.

The multiplication of $I(t)$ and $\frac{1-e^{-k}}{k}$ is C in $I(t)$ retained in use at the end of year t after decomposition.

Year 1900 is chosen as the initial year with $C(1900) = 0$, based on the assumption that contributions to the current year's HWP C stock and emissions due to HWP entering the HWP pool prior to 1900 are insignificant (IPCC 2006).

Using Equation (4), C stocks for HWPs in use in a given year can be estimated by HWP type and end use. The sum of C stocks calculated by product type and end use is the total C stock of the in-use HWPs produced by the Canadian forestry sector at the end of the year.

4. End-of-life analysis – carbon stock and emissions of Canada's retired harvested wood products

4.1. Disposal of retired harvested wood products

The C stocks in HWPs depend not only on the product's service life but also its disposal. A retired HWP can be recycled, burned with or without energy recovery, disposed of in dumps or landfills, or composted (Figure 5). Recycled HWPs continue to store C, while burning retired HWPs releases C to the atmosphere. Emissions are reduced if burning replaces fossil fuel and if the energy from combustion is recovered. When HWPs are disposed of in landfills, they decompose slowly releasing C to the atmosphere, with about half emitted as CH_4 (IPCC 2006). Thus, the after-service fate of HWPs is an important consideration with potentially dramatic differences in associated C stocks and emissions.

Because of a lack of Canadian data on the fate of HWPs after use, we adapted the U.S. HWP disposition estimated by Skog (2008) for HWPs produced in Canada (Tables 21 and 22). Paper recycling rates in Canada were similar to those in the United States (Statistics Canada 2005, p. 11, Figure 2.2; Environmental Paper Network 2011, p. 4). We added the 2007 and 2009 recycling rates of 58 and 66%, respectively, as estimated by the Forest Products Association[10] (Table 22). We assumed that the fraction of paper and paper products disposed of in landfills decreased as a result of increased recycling, while keeping the fractions of other disposal options constant.

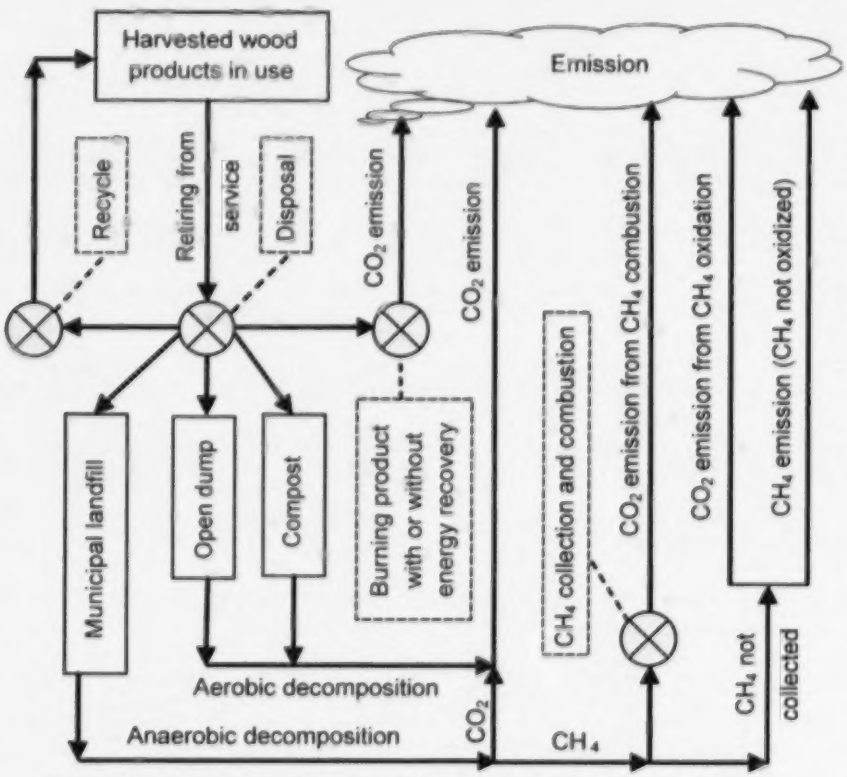

Figure 5. *Carbon conversion from harvested wood products (HWPs) beyond the end of their service lives.*

[10] Available from <www.fpac.ca/publications/fpac-sustainability-2011-en-final.pdf>. Accessed Sep. 14, 2012.

4.2. Harvested wood product carbon emission and retention in compost, dumps, and landfills

4.2.1. Carbon emission and retention of discarded harvested wood products

In North America prior to 1980, a significant portion of retired HWPs were disposed of in open dumps (Hettiaratchi 2007; Tables 21 and 22), which are shallower than modern landfills. Waste in dumps could be left in open piles, often loosely compacted, with moisture and oxygen available to allow HWPs to decompose more completely and aerobically, with little CH_4 production compared to landfills (IPCC 2006, p. 3.16). Skog (2008) assumed that HWPs disposed of in open dumps decompose completely over time. In comparison, the IPCC (2006, Table 3.1, p. 3.14) suggested that in shallow open dumps (<5 m waste), 40% of organic waste decomposes under anaerobic conditions producing CH_4, and the remaining 60% decomposes under aerobic conditions.

In managed landfills, discarded waste is usually covered and compacted mechanically, creating conditions for anaerobic decomposition. In an anaerobic environment, a portion of the buried HWP does not decompose at all or decomposes extremely slowly (IPCC 2006). Carbon dioxide (CO_2) and CH_4 each roughly account for 50% of HWP C that decomposes anaerobically (Pingoud and Wagner 2006).

The first-order decay model for estimating C in HWP in use (described in Section 4.3.1), can also be used to estimate HWP C stock in landfills and dumps. Skog (2008) assumed all HWP C decomposes over time in open dumps, and thus the fraction of HWP C that ultimately decomposes, D_f, equals 100% for HWP disposed of in open dumps. For HWP disposed of in managed landfills, the IPCC (2006) suggested a default D_f value of 0.5 when country-specific data are not available. This default was used by Environment Canada (2011; p. 199) for landfills used by HWP industries. But information in FAO (2011; p.53) indicated that this default value can significantly overestimate the decomposition of wood in landfills, as 80% of solid HWP C and 50% of that in paper and paper products does not decompose under anaerobic conditions.

Table 21. *Percentages of retired Canadian solid harvested wood products that were burned (with or without energy recovery), recycled, composted, or disposed of in landfills or dumps (modified from Skog 2008).*

Year	Burned	Recycled	Composted	Landfilled	Disposed of in dump
1900-1920	29	0	0	0	71
1940	30	0	0	3	67
1950	30	0	0	7	63
1960	31	0	0	11	58
1970	21	0	0	26	53
1980	9	0	0	68	23
1990	16	7	2	74	2
2000-2010	14	9	8	67	2

Table 22. *Percentages of retired Canadian paper products that were burned (with or without energy recovery), recycled, composted, or disposed of in landfills or dumps (modified from Skog 2008).*

Year	Burned	Recycled	Composted	Landfilled	Disposed of in dump
1900-1920	29	0	0	0	71
1940	30	0	0	3	67
1950	30	0	0	7	63
1960	31	17	0	9	44
1970	21	15	0	21	43
1980	9	21	0	52	17
1990	16	28	2	54	1
2000	16	43	5	32	1
2007	16	58	5	20	1
2009	16	66	5	12	1

Note: Recycling increased from 43% in 2000 to 66% in 2009 and the proportion of waste paper discarded in landfills decreased from 37% in 2000 to 12% in 2009, assuming other categories remained constant.

Table 23 lists D_f values and half-lives ($t_{1/2}$) for solid HWP and paper and paper products buried in landfills in the United States (Skog 2008). We applied these values to all HWPs from Canada, regardless of country where they were disposed of. Canada has two types of landfills: those that are used to dispose of municipal solid waste and those used by HWP industries for wood waste (Environment Canada 2011). The former were assumed to meet the criteria of managed solid waste disposal sites that create anaerobic conditions (Environment Canada 2007). Environment Canada (2011) also assumed HWP industrial landfills met the criteria of unmanaged deep solid waste disposal sites (≥5 m waste) (p. 152); such landfills create a partially anaerobic environment, in which 80% of the D_f portion of buried HWPs decompose under anaerobic condition, with half of the decomposed C becoming CH_4 (IPCC 2006; Vol. 5, Chap. 3, p 3.14, Table 3.1).

Table 23. *Fraction of harvested wood products (HWPs) that ultimately decomposes in landfills (D_f) and the half-life ($t_{1/2}$) of HWPs D_f in landfills and open dumps (from Skog 2008).*

	D_f in landfills	$t_{1/2}$ in landfills (years)	$t_{1/2}$ in dumps (years)
Solid HWPs	0.23	29	16.5
Paper products	0.56	14.5	8.25

Note: For open dumps, D_f = 100% for all HWPs

4.2.2. Landfill methane capture and oxidation

Some of the CH_4 generated by organic matter in landfills is oxidized to CO_2 by bacteria in soil covering the waste. For accounting purposes, the IPCC (2006) recommended a 10% oxidation rate for landfill CH_4 that reaches the top layer of soil. However, Chanton and Powelson (2009) found a mean CH_4 oxidation rate of 36±5%, indication the IPCC (2006) approach may significantly underestimate CH_4 oxidation and overestimate CH_4 emissions from landfills.

Methane can also be collected and combusted at landfills, with or without energy recovery. According to Environment Canada (2011, Table A3-48, p. 154), the ratio of captured CH_4 at municipal solid waste landfills in Canada increased from 20.8% in 1990 to 29.2% in 2009, as more landfills began collecting CH_4 (Environment Canada 2011; Figure 2-15, p. 70). Captured CH_4 used for energy recovery fell from 70% in 1997 to 51% in 2009, due to a greater number of facilities that initiated gas collection flaring captured CH_4 in preparation for using it to generate energy (Environment Canada 2011, p. 69). Thus, the energy recovery rate for captured landfill CH_4 could rebound in the future. Methane oxidation was not considered by Environment Canada (2011).

From 1990 to 2009 in the United States, CH_4 emissions from landfills decreased 20% due to reduced organic waste disposal and increased gas collection and combustion (US EPA 2011, p. 8-2). Landfill CH_4 collection in the United States increased from 11.1% in 1990 to 53.7% in 2009, which was significantly higher than that in Canada. On average, from 2000 to 2009, 23.4% of total CH_4 generated in U.S. municipal landfills was combusted for energy recovery and 28.3% was flared. From 2000 to 2009, on average, oxidation of CH_4 in the covering soil in landfills was 4.8% of the total generation or 10% of the remaining CH_4 after collection (US EPA 2011; p. 8-3, Table 8-4).

4.2.3. Calculating methane emissions from Canadian harvested wood products in landfills

Landfill CH_4 generation from decomposing HWPs in landfills can be estimated using the first-order decay model described as Equation 5 (IPCC 2006):

$$M_{gen} = C_{hwp} \times D_f \times (1 - (e^{-k})^t) \times M_f \qquad (5)$$

where M_{gen} is CH_4 generated by decomposition in landfills, C_{hwp} the C in HWPs, D_f the fraction of C_{hwp} that ultimately decomposes, k the decomposition constant calculated as $\frac{\ln(2)}{t_{1/2}}$ ($t_{1/2}$ is the half-life of D_f), t the years after disposal, and M_f the CH_4 fraction in landfill C emissions (0.5).

Landfill HWP C retention estimation consists of two components: the C retained in D_f and C in the fraction that will not decompose (1- D_f), as described in Equation 6:

$$C = C_{hwp} \times (1 - D_f) + C_{hwp} \times D_f \times (e^{-k})^t \quad (6)$$

Calculating potential landfill CH_4 emissions requires accounting for CH_4 generation, collection and oxidation, as described in Equation 7:

$$M_{emit} = (1 - R_{col}) \times M_{gen} \times (1 - R_{oxi}) \quad (7)$$

where M_{emit} is the potential landfill HWP CH_4 emission, R_{col} CH_4 collection rate, and R_{oxi} CH_4 oxidation rate (e.g., 0.10 as a conservative estimate; IPCC 2006).

Tables 24 and 25 are examples of HWP C retention and emissions in landfills for solid HWPs and paper and paper products produced using Canadian wood biomass, respectively, assuming 1 tonne annual HWP C disposal over a 100-year time span. Methane capture rates are weighted averages of the Canadian and U.S. rates based on the proportions of Canadian HWPs consumed by both markets and the landfill CH_4 capture rates in both countries in 2009: 0.439 and 0.457 for solid HWPs and paper and paper products, respectively. These CH_4 capture rates are slightly greater than the value of 0.40 estimated for disposed Canadian HWPs in landfills by Upton et al. (2007) for 2005. For solid HWPs and paper and paper products, rates of CH_4 capture are assumed to increase by 0.2% each year to 0.639 and 0.657 after 100 years, respectively. The IPCC default oxidation rate for the portion of CH_4 that reaches the covering soil in landfills, 10%, was used in the examples, but results of overall HWP C stock/emissions calculated using 36% oxidation rate (Chanton and Powelson 2009) were provided for comparison.

Disposing of 1 tonne of solid HWP C in a landfill each year will result in 85.7 tonnes of C retained in the landfill after 100 years, with CH_4 and CO_2 generation each accounting for half of the 14.3 tonnes of HWP C released through decomposition (Table 24). Of the 7.1 tonnes of C released as CH_4, 4 tonnes will be captured and 0.3 tonnes will be oxidized by bacteria in materials covering the waste. Thus, the eventual emission is 2.8 tonnes of C in 3.8 tonnes of CH_4, equivalent to 83.6 tonnes of CO_2 emission after considering the global warming potential of CH_4 (25 times that of CO_2; IPCC 2007b). To avoid double-counting of emissions, the landfill CH_4 emission is then reduced by the CO_2eq of the C contained in the CH_4. This is because C released as CO_2 is already accounted for by reducing landfill HWP C stock. Some of the CH_4 will be captured and burned to convert CH_4 to CO_2 with or without energy generation. The overall C stock of the solid HWPs in landfill is 230.8 tonnes CO_2eq at the end of the 100 years, after considering HWP C retention in the landfill (314.4 tonnes of CO_2eq) and CH_4 emission (83.6 tonnes of CO_2eq). However, if 36% of CH_4 oxidized when reaching the covering soil (as per Chanton and Powelson 2009), the overall C stock is 254.9 tonnes of CO_2eq.

As seen in Table 25, disposing of 1 tonne of C in paper and paper products in a landfill each year results in 55.6 tonnes of the C retained in the landfill by the end of 100 years, with 44.4 tonnes of C decomposing equally into CH_4 and CO_2. Of the 22.2 tonnes of C in CH_4, 12.7 tonnes is captured by collection systems and 0.95 tonnes oxidized by soil microorganisms. Thus, 8.4 tonnes of the C will be emitted as 11.4 tonnes of CH_4. Using the same calculation as for the solid HWP example, the net C stock in the landfill after disposing 1 tonne of paper and paper product C each year is -49.9 tonnes CO_2eq by the end of the 100-year period (negative values indicate emissions). However, if the CH_4 oxidation rate of the covering soil is assumed to be 36% (as per Chanton and Powelson 2009), the overall C stock is 23.4 tonnes of CO_2eq.

Table 24. *Net carbon (C) stock in landfills (tonnes of CO_2eq), assuming annual disposal of 1 tonne of solid harvested wood product (HWP) C.*

Year	10	20	30	40	50	60	70	80	90	100
C stock	9.75	19.06	28.03	36.72	45.21	53.53	61.72	69.80	77.80	85.74
Permanent C	7.70	15.40	23.10	30.80	38.50	46.20	53.90	61.60	69.30	77.00
Temporary C	2.05	3.66	4.93	5.92	6.71	7.33	7.82	8.20	8.50	8.74
CO_2eq of C stock	35.74	69.87	102.76	134.65	165.77	196.27	226.30	255.94	285.28	314.38
C in CH_4 emitted	0.06	0.23	0.46	0.75	1.07	1.41	1.77	2.12	2.47	2.82
C in CH_4 generated	0.13	0.47	0.99	1.64	2.39	3.24	4.14	5.10	6.10	7.13
C in CH_4 captured	0.06	0.22	0.47	0.80	1.20	1.66	2.18	2.74	3.35	4.00
C in CH_4 oxidized	0.01	0.03	0.05	0.08	0.12	0.16	0.20	0.24	0.27	0.31
CO_2eq of C in CH_4 emitted	0.23	0.83	1.70	2.76	3.94	5.19	6.48	7.78	9.07	10.33
Mass of CH_4 emitted	0.08	0.30	0.62	1.00	1.43	1.89	2.36	2.83	3.30	3.76
CO_2eq of CH_4 emitted	1.86	6.74	13.78	22.32	31.84	41.97	52.41	62.94	73.38	83.60
C in CO_2 emitted	0.13	0.47	0.99	1.64	2.39	3.24	4.14	5.10	6.10	7.13
Net C stock (CO_2eq)	33.87	63.13	88.98	112.34	133.93	154.30	173.89	193.00	211.90	230.78

Notes: Calculations were made using the following assumptions:
Under anaerobic conditions only a fraction of HWP C (degradable fraction, DJ) decomposes over time, and the rest stays in landfills permanently or decomposes extremely slowly. For solid HWPs, D_j = 0.23.
CO_2eq - Carbon dioxide equivalent.

Table 25. *Net carbon (C) stock in landfills (tonnes of of CO_2eq), assuming annual disposal of 1 tonne of paper and paper product C.*

Year	10	20	30	40	50	60	70	80	90	100
C stock	8.85	16.01	22.12	27.58	32.64	37.45	42.10	46.66	51.16	55.62
Permanent C	4.40	8.80	13.20	17.60	22.00	26.40	30.80	35.20	39.60	44.00
Temporary C	4.45	7.21	8.92	9.98	10.64	11.05	11.30	11.46	11.56	11.62
CO_2eq of C stock	32.46	58.71	81.12	101.14	119.69	137.31	154.37	171.08	187.57	203.93
C in CH_4 emitted	0.27	0.93	1.79	2.76	3.77	4.79	5.78	6.75	7.67	8.56
C in CH_4 generated	0.57	1.99	3.94	6.21	8.68	11.28	13.95	16.67	19.42	22.19
C in CH_4 captured	0.27	0.96	1.94	3.14	4.49	5.96	7.52	9.17	10.90	12.68
C in CH_4 oxidized	0.03	0.10	0.20	0.31	0.42	0.53	0.64	0.75	0.85	0.95
CO_2eq of C in CH_4 emitted	1.01	3.41	6.58	10.13	13.83	17.55	21.20	24.74	28.14	31.37
Mass of CH_4 emitted	0.37	1.24	2.39	3.68	5.03	6.38	7.71	9.00	10.23	11.41
CO_2eq of CH_4 emitted	8.14	27.60	53.23	81.95	111.90	141.99	171.54	200.17	227.65	253.84
C in CO_2 emitted	0.57	1.99	3.94	6.21	8.68	11.28	13.95	16.67	19.42	22.19
Net C stock (CO_2eq)	24.31	31.11	27.88	19.19	7.78	-4.67	-17.17	-29.09	-40.08	-49.91

Note: Calculations were made using the following assumptions: Under anaerobic conditions only a fraction of HWP C (degradable fraction, D_j) decomposes over time, and the rest stays in landfills permanently or decomposes extremely slowly. For paper and paper products, D_j = 0.56.
CO_2eq - Carbon dioxide equivalent.

5. Summary and application

We investigated the methods and parameters used to quantitatively analyze the C stocks and flows throughout the life cycle of HWPs produced in Ontario and Canada during the period 1999 to 2010. Key findings from the study are summarized here for the three major lifecycle stages in our analysis: forestry sector, end use, and disposal.

In the forestry sector analysis, C conversions that occurred during the period from the industrial roundwood stage to the finished HWP stage were analyzed by manufacturing processes, and described by process-based conversion parameters. The industrial roundwood consumption, estimated from the annual HWP production by using these conversion parameters, closely matched the annual industrial roundwood harvesting in Ontario and Canada. As a result, the conversion parameters and the analysis methods presented are considered reasonably accurate. We estimated that more than 90% of wood biomass harvested in these two jurisdictions was either contained in HWPs or burned to produce energy, indicating the high efficiency of the HWPs industries in utilizing harvested wood. Mill residue used in producing energy was estimated to account for 29 and 26% of industrial roundwood in Ontario and Canada, respectively. This use resulted in significant reductions in GHG emissions through: (i) reduced wood biomass entering industrial landfills and thus reduced landfill CH_4 emissions, and (ii) avoided emissions by using the bioenergy produced from mill residue to replace on-site fossil fuel energy production and/or purchased electricity.

In the end use analysis, we estimated that the U.S. and Canadian markets combined consumed 91% of Canada's solid HWPs from 2005 to 2010 and 68% of Canadian pulp and paper products in the period 1991 to 2010, and even greater fractions of the HWPs produced in Ontario. Thus, these two markets greatly influenced the overall end uses, service lives, and end-of-life disposal for HWPs from Ontario and Canada. The construction industry was the single most important solid HWP end user, consuming 65 and 62% of solid HWPs produced in Ontario and Canada, respectively, in the period 2005 to 2010. Using HWPs to replace other energy-intensive materials such as aluminum and cement in construction reduces GHG emissions. At the same time, HWPs used in construction can retain their C for a long period, resulting in increasing C stocks of HWPs in use.

Disposal options largely determine the post-disposal C dynamics of HWPs after they reach the end of their service lives. Prior to 1970, more than 74% of retired HWPs in North America were either burned or disposed of in open dumps. Starting from 1970, landfills quickly replaced open dumps in both Canada and the United States. In landfills, 56% of C in paper products was estimated to decompose, with a half-life of 14.5 years. In comparison, only 23% of solid HWP C was estimated to decompose, with a 29-year half-life. Thus, landfilled paper products have greater potential to produce CH_4 than solid HWPs. Paper recycling, an effective GHG mitigation option, increased from 21% in 1970 to 66% in 2009 in North America, resulting in the fraction of waste paper disposed of in landfills decreasing from more than 50% in 1980-1990 to 12% in 2009. As a part of the mitigation effort, landfill CH_4 collection and combustion increased significantly from 1990 to 2010, from 21 to 29% in Canada and from 11 to 54% in the United States. About half of the CH_4 collected in North America was burned to generate energy, resulting in avoided emissions from reduced consumption of fossil fuel energy.

We systematically compiled a comprehensive study that covered the major life stages of the main types of HWPs produced in Ontario and Canada. Results and conclusions from this study help to answer questions such as whether the HWP sectors in these two jurisdictions are a source of GHG emissions or contribute to GHG mitigation. As well, the results can be used to identify mitigation opportunities for Ontario's and Canada's HWP industries. Integrating the compiled information into a consistent and progressive format that follows the life cycle of HWPs allows the results to be applied to case studies that focus on a specific HWP type at one or more of its life stages. This could include, for example, estimating the amount of biomass C removed from the forest by harvesting, production of HWPs by category, biomass C used to produce bioenergy, biomass C contained in different types of HWPs with different end uses and their C stock changes over time, as well as landfill HWP C retention and emission. Therefore, the study results could be used in decisionmaking in forest resource management and policy development related to increasing C stocks and reducing emissions in Ontario and Canada.

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Appendix 1. Bark expansion factors for major tree species groups in Ontario

Bark expansion factor is defined as the sum of biomass of stem wood and stem bark divided by the biomass of stem wood. Bark expansion factors were estimated for six major tree species groups in Ontario, including eastern white pine, red pine, jack pine, spruce-fir, aspen-birch, and maple-beech-birch. For each species group, bark expansion factors were first estimated for individual species based on the cited references; the arithmetic mean of all factors for a species group was calculated and used as the bark expansion factor for the group (Table A1).

Table A1. *Estimates of bark expansion factors in industrial roundwood for major tree species groups in Ontario.*

Species group*	Expansion factor	Average expansion factor†	Species	Region	Reference
Eastern white pine	1.15	1.133	Eastern white pine	Canada	Lambert et al. 2005[2]
	1.15			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.10			Ontario, Canada	Peichl and Arain 2007
Red pine	1.10	1.091	Red pine	Canada	Lambert et al. 2005[2]
	1.08			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.09			Minnesota, U.S.A.	Alban et al. 1978
	1.10			Ontario, Canada	Alemdag 1982
Jack pine	1.09	1.090	Jack pine	Ontario, Canada	Alemdag 1982
	1.09			Canada	Lambert et al. 2005[2]
	1.08			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.12			Minnesota, U.S.A.	Alban et al. 1978
	1.08			Northwest T., Canada	Singh 1984a
	1.08			Prairie provinces, Canada	Singh 1984b
	1.10			Alberta, Canada	Monserud et al. 2006
Spruce-fir	1.11	1.137	Black spruce	Ontario, Canada	Alemdag 1982
	1.16			Canada	Lambert et al. 2005[2]
	1.14			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.08			Minnesota, U.S.A.	Alban et al. 1978
	1.14			Northwest T., Canada	Singh 1984a
	1.11			Prairie provinces, Canada	Singh 1984b
	1.12		White spruce	Ontario, Canada	Alemdag 1982
	1.15			Canada	Lambert et al. 2005[2]
	1.11			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.12			Northwest T., Canada	Singh 1984a
	1.12			Prairie provinces, Canada	Singh 1984b
	1.14		Balsam fir	Ontario, Canada	Alemdag 1982
	1.18			Canada	Lambert et al. 2005[2]
	1.13			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.18			Newfoundland, Canada	Moroni et al. 2005
	1.16			Prairie provinces, Canada	Singh 1984b

Table A1. Con't.

Aspen-birch	1.18	1.202	Trembling aspen	Ontario, Canada	Alemdag 1982
	1.22			Canada	Lambert et al. 2005[2]
	1.16			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.23			Minnesota, U.S.A.	Alban et al. 1978
	1.21			Northwest T., Canada	Singh 1984a
	1.21			Prairie provinces, Canada	Singh 1984b
	1.21		Balsam poplar	Canada	Lambert et al. 2005[2]
	1.25			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.27			Northwest T., Canada	Singh 1984a
	1.18		White birch	Ontario, Canada	Alemdag 1982
	1.17			Canada	Lambert et al. 2005[2]
	1.14			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.16			Prairie provinces, Canada	Singh 1984b
Maple-beech-birch	1.13	1.106	Red maple	Canada	Lambert et al. 2005[2]
	1.14			Upper Great Lakes, U.S.A.	Perala and Alban 1994[3]
	1.10			Quebec, Canada	Quellet 1985
	1.13		Yellow birch	Canada	Lambert et al. 2005[2]
	1.17			Upper Great Lakes, U.S.A.	Ter-Mikaelian and Korzukhin 1997[2]
	1.12			New Hampshire, U.S.A	
	1.07		American beech	Canada	Lambert et al. 2005[2]
	1.08			New Brunswick, Canada	Ter-Mikaelian and Korzukhin 1997[2]
	1.06			New Hampshire, U.S.A	
	1.06			Quebec, Canada	Quellet 1985

Notes: [1] An average factor for a species group was calculated as the arithmetic mean of all factors reported for individual species in the cited references.

[2] DBH-based equations from these sources were used to estimate the biomass of stem wood and stem bark, from which the bark expansion factors were calculated; DBH was the mid-point value of the DBH ranges specified in the cited references.

[3] Basic DBH- and height-based equations from this source were used to estimate the biomass of stem wood and stem bark, from which the bark expansion factors were calculated; DBH was the mid-point values of the DBH ranges specified in the references, height was the site index at 50 years from the cited reference if available, when a site index was not provided in the reference, the mid-point value of the DBH range was used.

We attempted to include only forests of harvestable age. For sources that provided equations, the average diameter at breast height and average height were used to estimate biomass of merchantable stem wood and bark, as specified above.

For other sources listed in the table, quantitative estimates of stem wood and stem bark were presented, and were directly used in calculating the bark expansion factors.

Scientific names of tree species: eastern white pine – *Pinus strobus* L.; red pine – *Pinus resinosa* Ait.; jack pine – *Pinus banksiana* Lamb.; black spruce – *Picea mariana* (Mill.) BSP; white spruce – *Picea glauca* (Moench) Voss; balsam fir – *Abies balsamea* (L.) Mill.; aspen – *Populus* spp.; trembling aspen – *Populus tremuloides* Michx.; balsam poplar – *Populus balsamifera* L.; white birch – *Betula papyrifera* Marsh.; red maple – *Acer rubrum* L.; beech – *Fagus grandifolia* Ehrh.; yellow birch – *Betula alleghaniensis* Britton.

Appendix 2. Production of solid harvested wood products in Ontario and Canada

Table A2. *Solid harvested wood product production (thousand m³) in Ontario from 1999 to 2010. (Data obtained from Christopher Clowater, 2012, Industry Relations Branch, OMNR, pers. comm.).*

Product	1999	2000	2001	2002	2003	2004
Lumber	7513.7	7603.2	7520.3	7578.0	7033.6	7285.9
Plywood	334.2	272.8	303.9	348.8	292.9	310.5
OSB	1948.5	2000.7	2015.3	2083.7	2215.5	2149.9
MDF	0.0	250.7	10.9	502.6	474.4	511.5
Particleboard	227.2	196.1	553.8	469.2	356.9	494.0
Product	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Total	**10023.5**	**10323.3**	**10404.2**	**10982.4**	**10373.4**	**10751.8**
Lumber	7564.9	6418.9	6043.0	17,644.8[1]	2406.7	2358.6
Plywood	12,980.0[1]	214.6	183.9	66.8	54.9	28.1
OSB	2175.2	1824.7	1222.9	1078.8	405.5	982.5
MDF	288.5	291.8	271.8	273.1	298.1	277.8
Particleboard	463.9	431.0	147.1	136.5	159.5	178.0

Note: [1] The production of plywood in 2005 and lumber in 2008 are much larger than all other years, and were considered suspect; they were not used in calculating average annual production.

Table A3. *Percentage of each type of solid harvested wood product in Ontario from 1999 to 2010.*

Product	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Lumber	75.0	73.7	72.3	69.0	67.8	67.8	70.6	69.9	76.8	80.2	72.4	61.7
Plywood	3.3	2.6	2.9	3.2	2.8	2.9	2.0	2.3	2.3	0.8	1.7	0.7
OSB	19.4	19.4	19.4	19.0	21.4	20.0	20.3	19.9	15.5	13.7	12.2	25.7
MDF	0.0	2.4	0.1	4.6	4.6	4.8	2.7	3.2	3.5	3.5	9.0	7.3
Particleboard	2.3	1.9	5.3	4.3	3.4	4.6	4.3	4.7	1.9	1.7	4.8	4.7

Note: Calculated using production data in Table A2, Appendix 2.

OSB – oriented strandboard; MDF – medium density fibreboard.

Table A4. *Solid harvested wood product (HWP) production (thousand m³) in Canada from 1991 to 2010.*

Product	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Lumber-SW[1]	50,644	54,605	58,442	61,228	61,573	63,898	65,015	63,808	72,895	75,213
Lumber-HW[1]	974	1,104	1,106	1,181	1,003	883	1,062	1,002	1,164	1,527
Plywood[2, 4]	2,206	2,339	2,325	2,335	2,332	2,315	2,331	2,550	2,729	2,844
OSB[3]	1,068	1,820	2,276	2,514	2,825	4,296	5,153	6,073	6,808	6,841
MDF[2]	384	382	430	474	717	894	1,056	1,245	1,741	1,833
Particleboard[2]	2,650	3,557	4,173	4,493	5,309	6,754	7,961	8,621	10,130	10,364
Year total	57,926	63,807	68,752	72,225	73,759	79,040	82,578	83,299	95,467	98,622
Product	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Lumber-SW[1]	72,036	77,953	77,535	82,774	81,172	79,228	70,641	56,139	44,436	52,356
Lumber-HW[1]	1,598	1,851	1,785	1,816	1,717	1,642	1,401	1,111	813	955
Plywood[2, 4]	2,626	2,876	2,906	3,204	3,202	3,152	3,239	2,725	2,260	2,423
OSB[3]	7,364	7,505	8,184	8,964	9,015	9,241	6,942	3,886	3,126	3,545
MDF[2, 5]	1,927	1,967	1,962	2,130	1,912	1,947	1,987	1,519	1,361	1,314
Particleboard[2]	10,718	11,250	11,623	11,285	12,467	12,534	12,411	7,976	5,539	6,157
Year total	96,269	103,402	103,995	110,173	109,485	107,744	96,621	73,356	57,534	66,750

Note: [1] Data obtained from the Natural Resources Canada's (NRCan) database <cfs.nrcan.gc.ca/statsprofile/production>. SW – softwood; HW – hardwood.

[2] Data obtained from the United Nations Food and Agriculture Organization database (FAOSTAT) <faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor>.

[3] Oriented strandboard (OSB) production is calculated as the difference of the combined production of plywood and OSB obtained from NRCan database and the plywood production from FAOSTAT database.

[4] Plywood production listed is the sum of plywood and veneer sheet production from FAOSTAT database.

[5] Medium density fibreboard (MDF) production is the total of hardboard, MDF, and insulating board from FAOSTAT database (density: insulating board 0.35-0.50 g/cm³; MDF 0.5-0.8 g/cm³; hardboard exceeds 0.80g/cm³).

Table A5. *Percentage of major solid harvested wood product (HWP) types in Canada from 1991 to 2000.*

Product	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Lumber	89.1	87.3	86.6	86.4	84.8	82.0	80.0	77.8	77.6	77.8
Plywood	3.8	3.7	3.4	3.2	3.2	2.9	2.8	3.1	2.9	2.9
OSB	1.8	2.9	3.3	3.5	3.8	5.4	6.2	7.3	7.1	6.9
MDF	0.7	0.6	0.6	0.7	1.0	1.1	1.3	1.5	1.8	1.9
Particleboard	4.6	5.6	6.1	6.2	7.2	8.5	9.6	10.3	10.6	10.5
Product	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Lumber	76.5	77.2	76.3	76.8	75.7	75.1	74.6	78.0	76.6	79.9
Plywood	2.7	2.8	2.8	2.9	2.9	2.9	3.4	3.7	3.9	3.6
OSB	7.6	7.3	7.9	8.1	8.2	8.6	7.2	5.3	5.4	5.3
MDF	2.0	1.9	1.9	1.9	1.7	1.8	2.1	2.1	2.4	2.0
Particleboard	11.1	10.9	11.2	10.2	11.4	11.6	12.8	10.9	9.6	9.2

Note: Calculated using production data in Table 7.
OSB – oriented standboard; MDF – medium density fibreboard.

Appendix 3. Forest harvesting in Ontario and Canada

Table A6. *Net merchantable volume harvested (000 m³) from Ontario's and Canada's forests from 1999 to 2010. (Data obtained from Canada's National Forestry Database available at <http://www.nfdp.ccfm.org/products/jurisdictional_e.php>. Accessed on Sept. 15, 2012.)*

	Ontario			Canada		
Year	Logs	Pulpwood	Total	Logs	Pulpwood	Total
1999	17,987	6,769	24,756	168,567	26,788	195,355
2000	20,005	7,989	27,993	170,218	28,699	198,917
2001	19,878	4,124	24,001	159,866	23,079	182,945
2002	19,481	6,716	26,197	167,686	25,557	193,243
2003	16,875	7,323	24,197	150,371	27,841	178,211
2004	17,833	7,144	24,961	176,816	28,313	205,129
2005	18,250	4,925	23,152	176,808	23,442	200,250
2006	16,223	4,336	20,542	157,632	23,423	181,054
2007	10,194	5,703	15,890	137,471	23,919	161,390
2008	6,606	5,223	11,823	112,897	23,199	136,095
2009	5,761	3,865	9,626	93,674	21,867	115,541
2010	7,497	5,286	12,783	118,438	23,189	141,627
Percentage	71.8	28.2	100.0	85.7	14.3	100.00

Note: The category 'logs' is the combination of 'logs and bolts' and 'other industrial roundwood' in the data source.
Percentage of logs and pulpwood were calculated based on total harvest from 1999 to 2010.

Appendix 4. Production of pulp, paper, and paper products in Ontario and Canada

Table A7. *Market pulp production in Ontario (thousand ODT[1]) from 1999 to 2010 (Christopher Clowater, 2012, Industry Relations Branch, OMNR, pers. comm.).*

Year	Pulping process			Total
	Sulphate	Sulphite	Mechanical	
1999	1162.6	206.5	618.9	1988.0
2000	826.8	190.8	641.6	1659.1
2001	1065.7	162.5	429.3	1657.5
2002	1230.2	171.7	657.5	2059.4
2003	1226.4	171.2	640.5	2038.0
2004	2089.9	185.7	634.7	2910.3
2005	776.5	351.9	575.6	1703.9
2006	703.5	255.1	465.4	1424.0
2007	670.2	188.4	312.3	1170.9
2008	647.2	0.0	307.1	954.3
2009	350.0	0.0	278.0	628.1
2010	475.0	0.0	333.8	808.8

Note: [1] ODT: oven-dry tonne, i.e., 0% moisture content.

Table A8. *Production of paper and paper products (thousand ODT[1]) in Ontario from 1999 to 2010 (Christopher Clowater, 2012, Industry Relations Branch, OMNR, pers. comm.).*

Year	Product type			Total
	Fine Paper	Newsprint	Other paper[2]	
1999	760.3	979.9	861.0	2601.1
2000	831.5	1616.2	696.5	3144.3
2001	801.2	1155.5	1101.7	3058.4
2002	1221.7	1230.7	1029.9	3482.3
2003	1054.7	1166.8	1124.1	3345.6
2004	1115.9	1063.3	1194.7	3374.0
2005	724.4	811.2	929.5	2465.1
2006	630.9	739.1	390.2	1760.2
2007	453.5	647.1	377.0	1477.6
2008	442.6	501.7	173.3	1117.5
2009	215.6	324.1	124.6	664.3
2010	0.0	443.0	138.9	581.9

Note: [1] ODT: oven-dry tonne, i.e., 0% moisture content.
[2] Other paper: other paper and paper products made from chemical and/or mechanical pulp.

Table A9. *Production of market pulp (thousand ODT[1]) in Canada from 1999 to 2010. (Data available at <http://faostat.fao.org/site/626/default.aspx#ancor>. Accessed Sept. 21, 2012.).*

Pulp type	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Chemical[2]	12,248	12,415	11,868	12,260	12,309	12,323	11,603	10,558	10,287	9,319	7,796	8,424
Mechanical	10,100	11,106	10,247	10,459	10,771	10,925	10,809	10,227	9,529	8,668	7,295	7,973
Semi-chemical	496	506	455	468	503	533	484	429	444	439	413	402
Sub-total	22,844	24,026	22,599	23,187	23,584	23,781	22,896	21,214	20,260	18,446	15,504	16,799

Note: [1] Converted from air-dry tonne (i.e., 10% moisture content) used in the FAO database to oven-dry tonne (ODT, i.e., 0% moisture content).
[2] Chemical pulp includes bleached and unbleached sulphate and sulphite pulp and dissolving pulp.

Table A10. *Production of paper and paper products (thousand' ODT[1]) in Canada from 1991 to 2010. (Data available at <http://faostat.fao.org/site/626/default.aspx#ancor>. Accessed Sept. 21, 2012).*

Product type	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Newsprint	8,284	8,299	7,536	7,610	7,638	7,362	6,993	6,410	5,976	5,394	3,940	4,175
Printing and writing paper	5,112	5,715	5,523	5,698	5,810	6,318	6,035	5,503	5,352	4,739	3,986	3,658
Wrapping and packaging paper and paperboard	4,124	4,127	4,040	3,756	3,561	3,680	3,467	3,405	3,317	3,073	2,641	2,645
Household and sanitary paper and other paper and paperboard	723	722	752	1,003	957	1,055	1,055	1,054	986	1,004	974	982
Total	18,252	18,863	17,851	18,066	17,988	18,416	17,548	16,370	15,630	14,210	11,541	11,460

Note: [1] Converted from air-dry tonne (i.e., 10% moisture content) used in the FAO database to oven-dry tonne (ODT, i.e., 0% moisture content).

Appendix 5. Exports of Canada's harvested wood products

Table A11. *Fraction of Canadian solid harvested wood products (by volume) exported from 1999 to 2010.*

Product type	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Softwood lumber	-	-	0.735	0.783	0.772	0.777	0.733	0.739	0.666	0.649
Plywood[1]	0.212	0.275	0.291	0.355	0.485	0.505	0.502	0.555	0.636	0.618
MDF[2]	0.219	0.181	0.205	0.213	0.509	0.556	0.705	0.709	0.659	0.564
Particleboard	0.468	0.580	0.711	0.767	0.810	0.769	0.763	0.815	0.768	0.776
Product type	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Softwood lumber	0.679	0.641	0.655	0.665	0.681	0.664	0.632	0.587	0.584	0.580
Plywood[1]	0.713	0.672	0.637	0.647	0.676	0.604	0.500	0.403	0.314	0.289
OSB	-	-	-	-	0.888	0.880	0.759	0.727	0.680	0.654
MDF[2]	0.754	0.698	0.841	0.728	0.768	0.729	0.633	0.569	0.496	0.439
Particleboard	0.794	0.778	0.795	0.865	0.789	0.773	0.755	0.525	0.590	0.583

Note: [1] Plywood includes plywood and veneer sheet.

[2] Medium density fibreboard (MDF) includes hardboard, MDF, and insulating board.

Data sources: Softwood lumber obtained from CCFM (2006, updated data for Figure 5.1h) for the period 1993 to 2006, and from FPInnovations (2009, 2011) for the period 2007 to 2010; plywood, MDF, oriented strandboard (OSB), and particleboard obtained from FAOSTAT database.

Table A12. *Fractions of exported Canadian solid harvested wood products (by volume) consumed by the United States (FPInnovations 2009, 2011).*

Product	2005	2006	2007	2008	2009	2010	Average[1]
Softwood lumber	0.912	0.898	0.870	0.826	0.750	0.697	0.845
Plywood	0.910	0.947	0.870	0.765	0.974	0.785	0.885
OSB	0.990	0.980	0.920	0.900	0.894	0.852	0.944
MDF	0.955	0.947	0.885	0.910	0.936	0.923	0.928
Particleboard	0.999	0.997	0.990	0.997	0.997	0.997	0.996
Overall average[2]	0.924	0.912	0.878	0.837	0.774	0.721	0.861[1]

Note: [1] Average fraction calculated as the ratio of total Canadian solid HWPs consumed by United States divided by total exported Canadian solid HWPs by volume from 2005 to 2010.

[2] Overall average - the average annual fraction of all exported Canadian solid HWPs consumed by the United States by volume in a given year.

OSB – oriented strandboard; MDF – medium density fibreboard.

Table A13. *Export fractions of Canadian pulp and paper products by product type from 1991 to 2000.*

Product	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Chemical pulp[1]	0.646	0.646	0.684	0.675	0.677	0.665	0.705	0.697	0.720	0.730
Mechanical pulp	0.026	0.025	0.029	0.032	0.026	0.022	0.025	0.023	0.027	0.020
Newsprint	0.954	0.974	0.985	1.011[2]	0.993	0.955	0.955	0.899	0.898	0.921
Printing and writing paper	0.440	0.544	0.505	0.536	0.562	0.579	0.635	0.733	0.569	0.645
Wrapping and packaging paper	0.362	0.306	0.426	0.447	0.452	0.505	0.552	0.487	0.508	0.539
Household, sanitary and other paper products	0.142	0.175	0.186	0.166	0.138	0.136	0.182	0.168	0.178	0.145
Product	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Chemical pulp[1]	0.737	0.741	0.684	0.683	0.685	0.765	0.758	0.751	0.750	0.765
Mechanical pulp	0.023	0.021	0.019	0.012	0.008	0.009	0.008	0.007	0.005	0.005
Newsprint	0.930	0.963	0.977	0.942	0.943	0.941	0.906	0.961	0.901	0.957
Printing and writing paper	0.665	0.694	0.698	0.786	0.829	0.810	0.685	0.829	0.831	0.818
Wrapping and packaging paper	0.511	0.555	0.534	0.622	0.585	0.580	0.316	0.587	0.601	0.605
Household, sanitary and other paper products	0.159	0.154	0.145	0.177	0.185	0.200	0.180	0.189	0.176	0.191

Note: [1]Chemical pulp includes bleached and unbleached sulphate and sulphite pulp, and dissolving pulp.
[2]Export fraction greater than 1 indicates possible errors in export and/or production data.

Table A14. *Fractions of exported Canadian pulp and paper products consumed by major importers from 2005 to 2010 (based on monetary value reported by FPInnovations 2009, 2011).*

Product	2005	2006	2007	2008	2009	2010	Average
Pulp							
United States	0.449	0.428	0.425	0.449	0.409	0.411	0.429
Major Asian[1]	0.318	0.387	0.405	0.388	0.453	0.462	0.402
EU27[2]	0.180	0.131	0.112	0.093	0.072	0.069	0.110
Others	0.053	0.053	0.057	0.069	0.065	0.057	0.059
Paper products							
United States	0.857	0.857	0.832	0.807	0.832	0.799	0.833
EU27[2]	0.043	0.034	0.054	0.047	0.054	0.037	0.045
Others	0.100	0.109	0.114	0.146	0.114	0.164	0.122

Note: [1] Major Asian includes China, Japan, and South Korea.
[2] EU27 are the 27 countries of the European Union.

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